

## University of Groningen

### An optical and H i study of the dwarf Local Group galaxy VV124 = UGC4879

Bellazzini, M.; Beccari, G.; Oosterloo, T. A.; Galleti, S.; Sollima, A.; Correnti, M.; Testa, V.; Mayer, L.; Cignoni, M.; Fraternali, F.

*Published in:*  
Astronomy & astrophysics

*DOI:*  
[10.1051/0004-6361/201016159](https://doi.org/10.1051/0004-6361/201016159)

**IMPORTANT NOTE:** You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

*Document Version*  
Publisher's PDF, also known as Version of record

*Publication date:*  
2011

[Link to publication in University of Groningen/UMCG research database](#)

*Citation for published version (APA):*

Bellazzini, M., Beccari, G., Oosterloo, T. A., Galleti, S., Sollima, A., Correnti, M., Testa, V., Mayer, L., Cignoni, M., Fraternali, F., & Gallozzi, S. (2011). An optical and H i study of the dwarf Local Group galaxy VV124 = UGC4879: A gas-poor dwarf with a stellar disk? *Astronomy & astrophysics*, 527, [A58].  
<https://doi.org/10.1051/0004-6361/201016159>

#### Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

#### Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

*Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.*

# An optical and H I study of the dwarf Local Group galaxy VV124 = UGC4879

## A gas-poor dwarf with a stellar disk?

M. Bellazzini<sup>1</sup>, G. Beccari<sup>2</sup>, T. A. Oosterloo<sup>3,4</sup>, S. Galletti<sup>1</sup>, A. Sollima<sup>5,9</sup>, M. Correnti<sup>1</sup>,  
 V. Testa<sup>6</sup>, L. Mayer<sup>7,8</sup>, M. Cignoni<sup>1,10</sup>, F. Fraternali<sup>10</sup>, and S. Gallozzi<sup>6</sup>

<sup>1</sup> INAF - Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy  
 e-mail: michele.bellazzini@oabo.inaf.it

<sup>2</sup> European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei Munchen, Germany

<sup>3</sup> Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, The Netherlands

<sup>4</sup> Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV Groningen, The Netherlands

<sup>5</sup> Instituto de Astrofísica de Canarias, c/via Lactea s/n, La Laguna 38205, Spain

<sup>6</sup> INAF - Osservatorio Astronomico di Roma, via Frascati 33, 00040 Monteporzio, Italy

<sup>7</sup> Institute for Theoretical Physics, University of Zürich, Winterthurer-strasse 190, 9057 Zürich, Switzerland

<sup>8</sup> Institut für Astronomie, ETH Zürich-Hönggerberg, Wolfgang-Pauli-Strasse 16, 8093 Zürich, Switzerland

<sup>9</sup> INAF - Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy

<sup>10</sup> Dipartimento di Astronomia - Università degli Studi di Bologna, via Ranzani 1, 40127 Bologna, Italy

Received 17 November 2010 / Accepted 9 December 2010

### ABSTRACT

We present a detailed study of the dwarf galaxy VV124 (UGC4879), recently recognized as a remarkably isolated member of the Local Group. We have obtained deep ( $r \approx 26.5$ ) wide-field ( $23' \times 23'$ ) g,r photometry of individual stars with the LBC camera at the Large Binocular Telescope under sub-arcsec seeing conditions. The color-magnitude diagram suggests that the stellar content of the galaxy is dominated by an old, metal-poor population, with a significant metallicity spread. A very clean detection of the RGB tip allows us to derive an accurate distance of  $D = 1.3 \pm 0.1$  Mpc. Combining surface photometry with star counts, we are able to trace the surface brightness profile of VV124 out to  $\sim 5' \approx 1.9$  kpc radius (where  $\mu_r \approx 30$  mag/arcsec<sup>2</sup>), showing that it is much more extended than previously believed. Moreover, the surface density map reveals the presence of two symmetric flattened wings emanating from the central elongated spheroid and aligned with its major axis, resembling a stellar disk seen nearly edge-on. We also present H I observations obtained with the Westerbork Synthesis Radio Telescope (WSRT), the first ever of this object. A total amount of  $\approx 10^6 M_\odot$  of H I gas is detected in VV124. Compared to the total luminosity, this gives a value of  $M_{\text{HI}}/L_V = 0.11$ , which is particularly low for isolated Local Group dwarfs. The spatial distribution of the gas does not correlate with the observed stellar wings. The systemic velocity of the H I in the region superposed to the stellar main body of the galaxy is  $V_h = -25$  km s<sup>-1</sup>. The velocity field shows substructures typical of galaxies of this size but no sign of rotation. The H I spectra indicates the presence of a two-phase interstellar medium, again typical of many dwarf galaxies.

**Key words.** galaxies: dwarf – Local Group – galaxies: structure – galaxies: stellar content – galaxies: ISM – galaxies: individual: UGC4879

## 1. Introduction

Until just a few years ago, VV124 = UGC4879<sup>1</sup> was considered a unassuming isolated dwarf galaxy, classified as spheroidal/irregular, at a distance of  $D \sim 10$  Mpc (James et al. 2004). Integrated multi-color optical photometry was obtained by Jansen et al. (2004a) and Taylor et al. (2005), and  $J$  and  $K_S$  images were obtained by Grauer et al. (2003), within large surveys of nearby galaxies. From inspection of a low resolution integrated optical spectrum, Jansen et al. (2004b) concluded that it was likely “a young post-starburst galaxy”. From the  $H_\alpha + N[\text{II}]$  equivalent width, Jansen et al. (2004b) estimated a total star formation rate of  $0.005 M_\odot \text{ yr}^{-1}$  (assuming distance of 10 Mpc).

The generally adopted distance of  $D \sim 10$  Mpc was based entirely on the redshift estimate reported by the CfA survey ( $cz = 600$  km s<sup>-1</sup>; Huchra et al. 1983). A team of russian

scientists (Kopylov et al. 2008, K08 hereafter), triggered by the apparent partial resolution of VV124 into stars in Sloan Digital Sky Survey images (SDSS, Adelman-McCarthy et al. 2008), carefully searched public databases and the literature, eventually making the case for a much lower recession velocity and a much smaller distance for VV124. They followed up this smart intuition with deep  $V, I$  photometry and low-resolution spectroscopy and were actually able (a) to resolve the galaxy into individual stars down to  $\sim 2$  mag below the red giant branch (RGB) tip, thus obtaining a direct distance estimate of  $D = 1.1$  Mpc from the tip itself, and (b) to obtain a new estimate of the heliocentric velocity, much lower than the CfA value,  $V_h = -70 \pm 15$  km s<sup>-1</sup> (throughout the paper  $V_h$  stands for heliocentric radial velocity). This meant that K08 had found a new member of the Local Group (LG), since with the newly determined distances and velocity VV124 is found to lie near the turn-around radius of the LG, and, in fact, being its most isolated member. The galaxy

<sup>1</sup> A09125+5303 in the nomenclature adopted by Jansen et al. (2004a).

has a remarkable elliptical shape and ranks among the brightest LG dwarf spheroidal/transition type galaxies ( $M_B = -11.6$ ). The stellar budget of the galaxy seems dominated by old stars (RGB; age  $\geq 2$  Gyr) with colors compatible with low metallicity ( $Z \approx 0.001$ ). However, a sprinkle of bright blue stars, and the identification of an H II region, led K08 to conclude that VV124 is a transition type between dwarf irregulars (dIrr) and dwarf spheroidals (dSph), like Phoenix, Antlia or LGS3 (Mateo 1998). The results by K08 were further discussed in more detail in Tikhonov et al. (2010, T10 hereafter).

According to K08, the location and the peculiar velocity of VV124 indicate that it has never been a satellite of a major galaxy of the LG, hence it evolved in full isolation for a Hubble time. Therefore, VV124 may contain a fossil record of precious information on the initial conditions of dwarf galaxies. It may be considered as a possible progenitor of the gas-less amorphous dSphs found in the vicinity of the Milky Way or M 31, whose evolution has been likely largely driven by the strong interaction with the large galaxy they are orbiting around (see Mateo 1998; Lokas et al. 2010a, and references therein). In particular, Mayer et al. (2006, 2007) have developed a detailed model, within a modern cosmological context, in which dSphs are produced by the morphological transformation of dwarf disk galaxies by tidal stirring and ram-pressure stripping during their path through the halo of the main galaxy they are gravitationally bound to (see also Kormendy et al. 2008, and references therein for a more general view on the nature and origin of dSphs). As we shall see, VV124 may possibly share some remarkable characteristics with the precursors of modern dSphs envisaged in this model.

The general interest in isolated galaxies as objects of undisturbed evolution is witnessed, for example, by the large *Hubble* space telescope (HST) programme LCID (Gallart 2008), aimed at the determination of the star formation history in the center of six isolated LG dwarfs of various morphological types. Here we are more interested in the structure and dynamics of a galaxy that should be untouched by the interactions with other large galaxies since the beginning of time. In particular, the image presented in Fig. 1 of K08 suggests that the galaxy may be more extended than what could be enclosed into the  $6' \times 6'$  field studied by those authors. For these reasons, we acquired much deeper observations on a much wider field with the  $2 \times 8.4$  m Large Binocular Telescope (LBT, Mt. Graham – AZ). A beautiful color image derived from these data is presented in Fig. 1, giving also an idea of the number and variety of background galaxies that can be found in such deep LBT images. In this paper we describe and discuss the results of these observations, as well as those from deep H I data obtained with the Westerbork Synthesis Radio Telescope (WSRT) and from low resolution optical spectroscopy obtained with the Telescopio Nazionale Galileo (TNG).

The plan of the paper is the following: in Sect. 2 we present the LBT observations, we describe the reduction of these data and the artificial stars experiments. The process of surface photometry of the innermost regions of the main body of the galaxy is described, and the adopted system of local coordinates is also introduced. In Sect. 3 we discuss the derived color-magnitude diagrams (CMD), we provide a revised estimate of the distance to VV124 and we analyze the stellar content of the galaxy. Section 4 is devoted to the analysis of the surface brightness profile and the surface density distribution, while in Sect. 5 the results of the H I observations are discussed in detail; the derived H I velocity field is compared to the velocities obtained from low resolution optical spectroscopy (Sect. 5.1). Finally, the overall results are summarized and discussed in a broader context in Sect. 6.

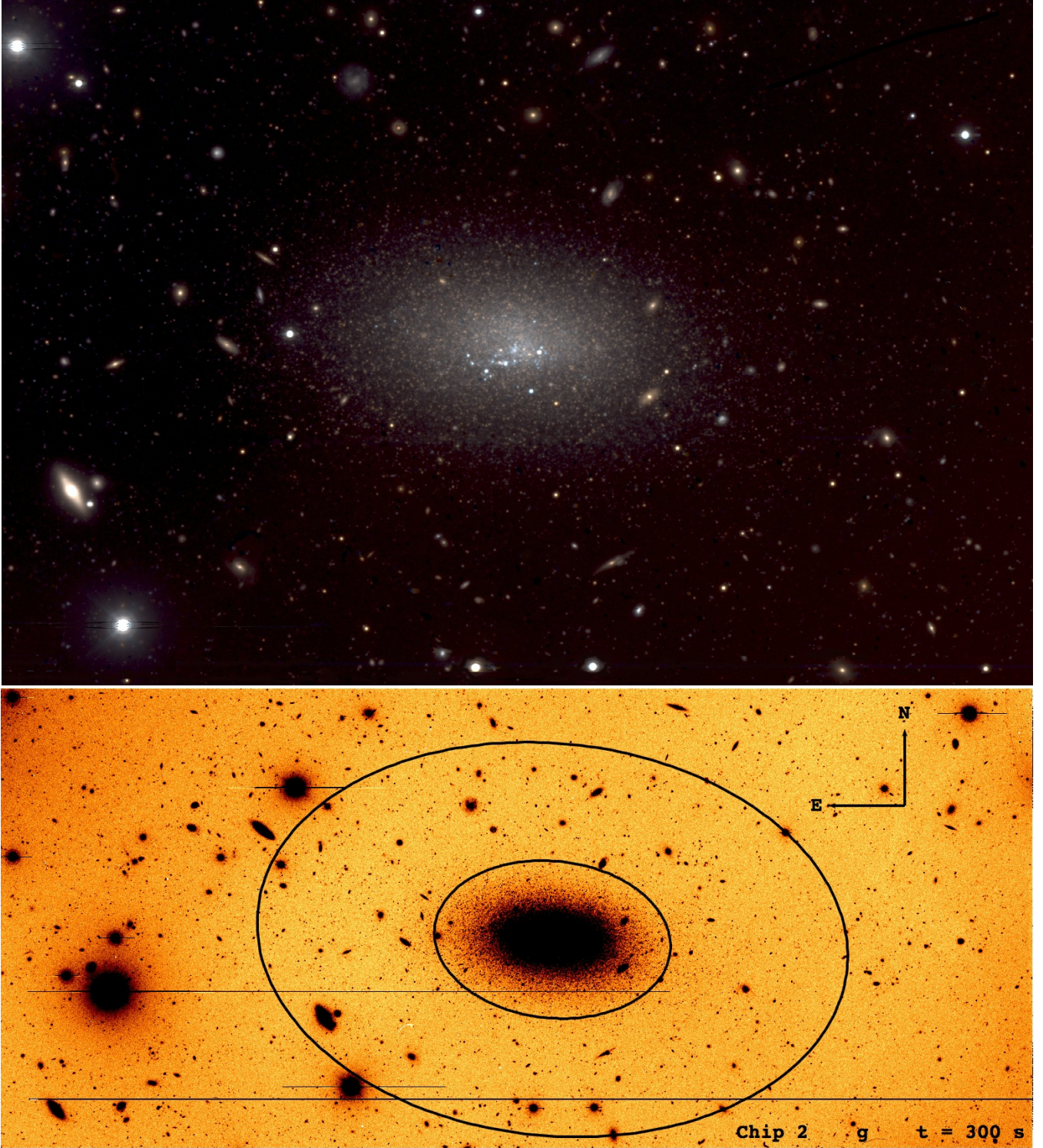
A few days before this manuscript was ready for submission, a preprint was posted on the *astro-ph* archive (Jacobs et al. 2011, hereafter J10), presenting deep HST / Advanced Camera for Surveys (ACS) photometry of VV124. This study turns out to be complementary to ours, as it focuses on the star formation history (SFH) in the innermost  $\approx 40''$  of VV124, a region essentially out of reach of our photometry because of the extreme crowding (see Sect. 2.3). We will briefly refer to the results by J10 in the following, when appropriate, but we do not discuss them in detail. In general, for the issues treated in both papers, the results of the two studies are in good agreement.

## 2. LBT observations and data reduction

Deep  $g$  and  $r$  photometry was acquired on the night of December 2, 2008, at LBT, using the blue channel of the Large Binocular Camera (Giallongo et al. 2008). LBC optics feed a mosaic of four  $4608 \text{ px} \times 2048 \text{ px}$  CCDs, with a pixel scale of  $0.225 \text{ arcsec px}^{-1}$ . Each CCD chip covers a field of  $17.3' \times 7.7'$ . Chips 1, 2, and 3 are flanking one another, being adjacent along their long sides; Chip 4 is placed perpendicular to this array, with its long side adjacent to the short sides of the other chips (see Fig. 4 of Giallongo et al. 2008). During our observations the pointing was chosen to place VV124 at the center of Chip 2, with the long side nearly aligned with the major axis of the galaxy (see Fig. 1). We will consider Chip 1 as our reference control field, sampling the back/foreground population in the direction of VV124; the CMDs from Chip 3 and Chip 4 are undistinguishable from that of Chip 1, hence do not provide any additional information relevant for our purposes. For this reason they will not be discussed anymore in the following. In the following, we will use the terms Chip 1(2) and field 1(2), abbreviated as f1 and f2, interchangeably. Several long ( $t_{\text{exp}} = 300 \text{ s}$ ) and short ( $t_{\text{exp}} = 20 \text{ s}$ ) exposures were acquired during the night, but we selected for the analysis only images taken under excellent seeing conditions, in particular: four  $t_{\text{exp}} = 300 \text{ s } g$  band images with seeing ranging from  $0.60''$  to  $0.69''$  and two  $t_{\text{exp}} = 300 \text{ s } r$  band images with seeing ranging from  $0.60''$  to  $0.62''$ . Three  $g$  and three  $r$   $t_{\text{exp}} = 20$  exposures were also reduced to provide a bridge between the photometry from our long exposures (reaching the saturation level at  $r \approx 19.0$ ) and the secondary calibrators from the SDSS R6 catalog (Adelman-McCarthy et al. 2008) that can be as faint as  $g, r \approx 23.0$  but have average photometric errors  $\sigma_g, \sigma_r \leq 0.03 \text{ mag}$  only for  $g, r \leq 20.0$ .

Relative photometry was performed independently on each image using the PSF-fitting code DAOPHOTII/ALLSTAR (Stetson 1987, 1994). Sources with peak higher than  $3\sigma$  above the background were identified in a stacked image obtained by registering and co-adding all the images considered for the analysis. Then, each of these stars was re-identified and fitted on each image (when possible). Only sources found at least in two  $g$  and two  $r$  images were retained in the final catalogue. The average and the standard error of the mean of the independent measures obtained from the different images were adopted as the final values of the instrumental magnitude and of the uncertainty on the relative photometry. To clean the catalog from spurious sources, we also adopted cuts in the image quality parameters *CHI* and *SHARP*, provided by DAOPHOTII. After accurate inspection of the distribution of measured sources in the planes mag vs. *CHI* and mag vs. *SHARP*, we decided to retain only sources having  $CHI \leq 2.0$  and  $-0.5 \leq SHARP \leq 1.5$ . This selection removed 2893 (1185) sources, leaving a final f2(f1) catalog of 15902 (7954) retained sources.





**Fig. 1.** *Upper panel:* color image of VV124 from the inner  $9' \times 6'$  of Chip 2. North is up, East to the left. *Lower panel:*  $g$  band image of the entire Chip 2, with VV124 near the center. The two overplotted ellipses have  $PA = 84.2^\circ$  and  $\epsilon = 0.44$ , as derived in Sect. 2.4, and semimajor axis of  $2'$  and  $5'$ , respectively.

### 2.1. Astrometry, photometric calibration and reddening

The instrumental positions, in pixels, were transformed into J2000 celestial coordinates by means of an astrometric solution (in the form of a first degree polynomial) obtained with CataXcorr<sup>2</sup> from 50(34) stars in common between the

f2(1) catalog and the SDSS DR6 catalogue; the r.m.s. scatter of the solution was  $\leq 0.3''$  in both RA and Dec.

The instrumental magnitudes ( $g_i$ ,  $r_i$ ) were transformed into the SDSS ugriz absolute photometric system ( $g_{SDSS}$ ,  $r_{SDSS}$ ;  $g$  and

<sup>2</sup> CataXcorr is a code aimed at cross-correlating catalogues and finding astrometric solutions, developed by Montegriffo at INAF - Osservatorio

Astronomico di Bologna, and successfully used by our group for the past 10 years.



$r$ , in the following, for simplicity) with the following equations

$$g_{\text{SDSS}} = g_i + 0.103(g_i - r_i) + 34.359 \quad (1)$$

$$r_{\text{SDSS}} = r_i - 0.062(g_i - r_i) + 33.911, \quad (2)$$

which were obtained from 43 stars with  $g < 20.0$  in common between our f2 catalogue and the SDSS DR6 catalog; the rms is 0.05 mag for both fits, implying an error on the zero point of  $\approx 0.01$  mag. The above equations have been obtained from stars covering the color range  $-0.37 \leq g - r \leq 1.55^3$ . The calibration of the photometry of the other fields (1, 3, and 4) was obtained by fine adjustments ( $\leq 0.05$  mag) of the zero point based on the handful of  $g < 20.0$  stars in common with the SDSS per field, keeping fixed the color coefficients of Eqs. (1) and (2). During the following analysis, in many instances we will have to compare observables in  $g, r$  with their counterparts in  $B, V, I$ . To do this we adopt

$$V = g - 0.579(g - r) - 0.01 \quad (\sigma = 0.005) \quad (3)$$

$$B = g + 0.313(g - r) + 0.227 \quad (\sigma = 0.011) \quad (4)$$

from Lupton (2005<sup>4</sup>),

$$I = r - 0.573(g - r) - 0.350 \quad (\sigma = 0.10) \quad (5)$$

valid for  $g - r < 1.4$ , and

$$g - r = -1.417 + 2.650(V - I) - 0.600(V - I)^2 \quad (\sigma = 0.06), \quad (6)$$

valid for  $0.8 \leq g - r \leq 1.4$ . Equations (5) and (6) have been derived by us from secondary standard stars in NGC 2419 (Bellazzini 2007).

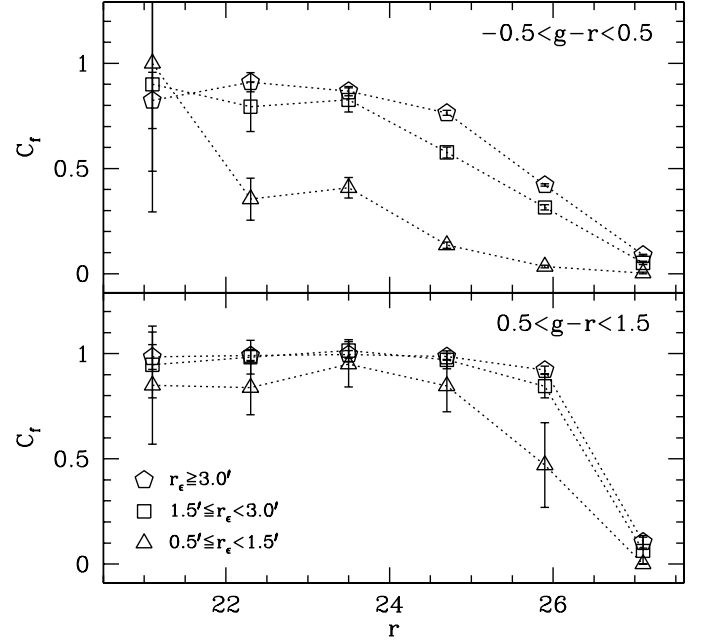
We interpolated the Schlegel et al. (1998) reddening maps to obtain an estimate of  $E(B - V)$  for each source included in our final f1 and f2 catalogues. For both fields we found an average  $E(B - V) = 0.015$  and a standard deviation  $\sigma_{E(B-V)} = 0.001$ . In agreement with previous studies we conclude that in the considered fields the reddening is very low and extremely uniform. In the following we always adopt  $E(B - V) = 0.015$  and the reddening laws  $A_g = 3.64E(B - V)$  and  $A_r = 2.71E(B - V)$ , derived by Girardi et al. (2004) for cool metal-poor giants.

## 2.2. Photometry of unresolved galaxies

To get some characterization of the background unresolved galaxies which are so abundant in these deep and wide high Galactic latitude fields, we reduced the best  $g$  and the best  $r$  images with SExtractor (Bertin & Arnouts 1996); the astrometric and photometric solutions were transferred from the DAOPHOTII catalog to this new catalog. SExtractor provides total magnitudes, central surface brightness (SB), ellipticity, position angle and other useful parameters for extended objects in astronomical images. Moreover, it provides a “stellarity” index, based on neural network analysis, whose value runs from  $s = 1.0$  for perfectly point-like sources (stars) to  $s = 0.0$  for obviously extended sources (galaxies). By inspection of the  $g$  vs.  $s$  plot we found that the discrimination made by SExtractor between point-like and extended sources is safe down to  $g \sim 23.5$  in our images, becoming increasingly blurred at fainter magnitudes. Hereafter we will refer to the catalog obtained with SExtractor and containing only sources with  $s < 0.5$  as to the GAL sample, since it should be dominated by background galaxies at any magnitude and it should include almost exclusively galaxies for  $g \leq 23.5$ . The GAL sample will be used in Sect. 3 to interpret the background contamination in the CMD of VV124.

<sup>3</sup> This range includes essentially all VV124 stars observed here (see Fig. 5).

<sup>4</sup> [www.sdss.org/dr4/algorithms/sdssUBVRITransform.html](http://www.sdss.org/dr4/algorithms/sdssUBVRITransform.html)

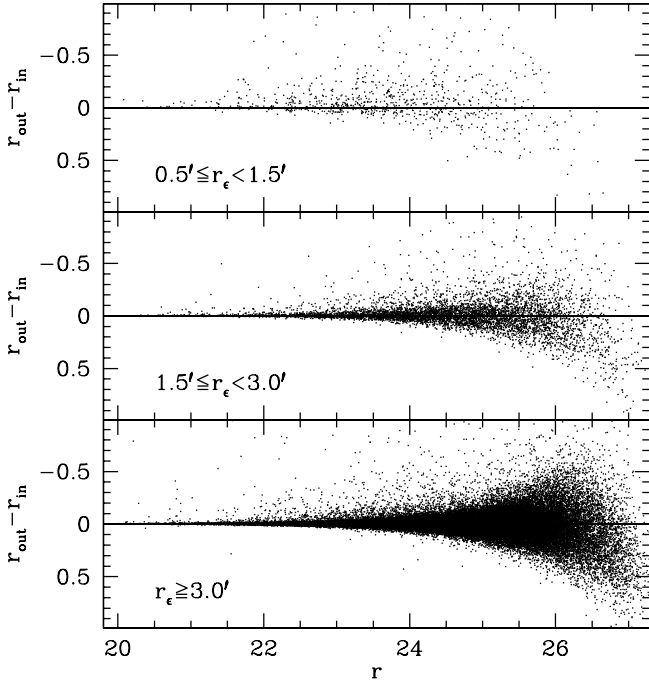


**Fig. 2.** Completeness fraction as a function of  $r$  magnitude for different color ranges (upper and lower panels) and for different (elliptical) radial ranges (different symbols).

## 2.3. Artificial stars experiments

The completeness of the stellar catalogs has been estimated by means of extensive artificial stars experiments. A total of 100 000 artificial stars have been added to the images (following the recipe described in Bellazzini et al. 2002a) and the entire data reduction process has been repeated as in the real case, also adopting the same selection criteria described above. The PSF adopted as the best-fit model for photometry was also assumed as the model for the artificial stars. Artificial stars were distributed uniformly in position, over the entire extent of f2, and in color, over the range  $-0.6 \leq g - r \leq 1.8$  (see Fig. 5, below). They were distributed in magnitude according to a luminosity function similar to the observed one but monotonically increasing also beyond the limit of the photometry, down to  $r \approx 27.5$  (see Bellazzini et al. 2002a, for details and discussion).

In Figs. 2 and 3, we show the completeness fraction ( $C_f$ ) as a function of  $r$  magnitude for different color ranges and for different (elliptical) radial ranges (see Sect. 2.4, for a definition of  $r_e$ ), and the difference between input and output  $r$  magnitudes for different (elliptical) radial ranges, respectively. It is interesting to note that in the color range covered by the RGB of VV124 ( $0.5 \leq g - r < 1.5$ , see Fig. 5), the completeness does not change with  $r_e$  for  $r_e > 1.5'$ ; in this range  $C_f$  is fairly constant and larger than 80% for  $r \leq 26.0$ . Finally, we note also that for  $r_e < 0.5'$  the completeness is lower than 50% virtually at any magnitude and the photometric errors due to crowding/blending becomes very significant. In agreement with these findings, in the observed catalogue there are only 129 stars in this radial range, nearly all brighter than  $r \approx 24.5$ . For these reasons, in the following we will limit our analysis to stars having  $r_e \geq 0.5'$ .



**Fig. 3.** Difference between input and output  $r$  magnitudes from artificial stars experiments in three different (concentric) elliptic annuli. The excess of stars with negative difference is due to blends: the recovered star is brighter because it is superposed to another source.

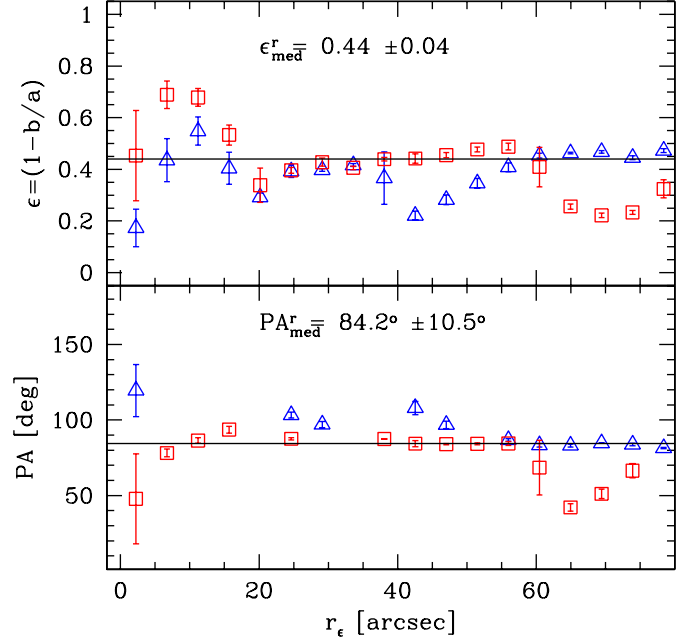
#### 2.4. Surface photometry and coordinate system

We performed surface photometry on the innermost 72'' of the best  $g$  and  $r$  images using XVISTA<sup>5</sup> (see Lauer 1985; Federici et al. 2007, for details on the code and on the adopted procedure). The derived surface brightness profile will be discussed in Sect. 3.3, below. For the purposes of the present section, we show in Fig. 4 the radial profiles of the ellipticity ( $\epsilon$ ) and of the position angle obtained with XVISTA by fitting ellipses to the observed light distribution (PA, measured anti-clockwise from north towards east). Over the considered radial range, both quantities are remarkably constant with radius, independent of adopted passband. For this reason, we adopted the average values ( $\pm$  the associated standard deviation) as our final estimates of  $\epsilon$  and PA, in particular  $\epsilon = 0.44 \pm 0.04$  and  $PA = 84.2^\circ \pm 10.5^\circ$ , in good agreement with the values reported by K08, Jansen et al. (2004b) and Taylor et al. (2005).

To obtain the coordinates of the center of the smooth elliptical light distribution of the main body of the galaxy (i.e. not affected by the asymmetric distribution of the young stars), we obtained a smoothed intensity contour within the central  $\approx 1'$  from the  $r$  and  $g$  images; next we fitted these contours with ellipses having  $\epsilon = 0.44$  and  $PA = 84.2^\circ$ , and we took the average of the coordinates of the centers of the ellipses fitted to the  $g$  and  $r$  images as our final center coordinates ( $\alpha_0, \delta_0$ )<sup>6</sup>. The  $g$  and  $r$  centers differ by 1.3''; we took the average of the two as our

<sup>5</sup> <http://astronomy.nmsu.edu/holtz/xvista/index.html>

<sup>6</sup> The final estimates are the result of the iteration of the described process: first XVISTA has been run by adopting a center position estimated by eye, thus obtaining an estimate of  $\epsilon$  and PA, then the center was estimated by fitting ellipses and XVISTA was run again with the newly determined center position. The process converged after the first iteration, i.e. the  $\epsilon$  and PA profiles were essentially unchanged by the adoption of new coordinates of the center.



**Fig. 4.** Ellipticity and position angle as a function of distance from the galaxy center along the major axis, from XVISTA surface photometry. Red open squares are from the analysis of the  $r$  image, blue open triangles are from the  $g$  image. Each plotted point is the mean of the considered quantities over a radial range of  $\pm 10$  px  $\approx \pm 2.2''$  around the position of the point, the errorbars are the associated standard deviations (as in Federici et al. 2007). In the lower panel we plotted only points having uncertainties in PA lower than  $30^\circ$ . Continuous horizontal lines mark the average levels of the parameters considered in each panel; the corresponding values are also reported.

final result. Our center is 11.2'' different (approximately in the E-N-E direction) from the coordinates provided by NED (and reported by K08 in their Table 1) and  $\sim 6''$  west from the center plotted by K08 in their Fig. 2. Tests on several images convinced us that our  $\alpha_0, \delta_0$  provide the best approximation for the center of the overall light distribution, as shown in the lower panel of Fig. 1, above. Adopting these coordinates for the center, we convert to cartesian coordinates  $X, Y$  (in arcmin) projecting the equatorial coordinates of each star ( $\alpha, \delta$ ) on the plane of sky as in van de Ven et al. (2006)

$$X' = -(10800/\pi) \cos(\delta) \sin(\alpha - \alpha_0)$$

$$Y' = (10800/\pi) [\sin(\delta) \cos(\delta_0) - \cos(\delta) \sin(\delta_0) \cos(\alpha - \alpha_0)]$$

with  $X'$  increasing toward west and  $Y'$  increasing toward north. These  $X', Y'$  coordinated were then rotated by  $90^\circ - PA$  into a  $X, Y$  system where the  $X$  axis is parallel to the major axis (and  $Y$  parallel to the minor axis) of the galaxy. Finally, we defined the elliptical distance from the center of the galaxy (or elliptical radius  $r_\epsilon$ ) as:

$$r_\epsilon = \sqrt{X^2 + \left(\frac{Y}{1 - \epsilon}\right)^2}$$

that is equivalent to the major-axis radius. The  $X, Y$  coordinate system and  $r_\epsilon$  will be always adopted in the following analysis.

**Table 1.** Observed and derived parameters of VV124.

Parameter	Value	Notes
$\alpha_0$	09:16:03.18	J2000
$\delta_0$	+52:50:31.3	J2000
$l_0$	164.6619°	Gal. long.
$b_0$	42.8864°	Gal. lat.
SGL	47.6121°	Supergal. long.
SGB	-15.0110°	Supergal. lat.
$E(B - V)$	$0.015 \pm 0.001$	
$(m - M)_0$	$25.61 \pm 0.13$	
$D$	$1.3 \pm 0.1$ Mpc	
1 arcsec	6.3 pc	conv. factor at $D = 1.3$ Mpc
$\epsilon$	$0.44 \pm 0.04$	
PA	$84.2^\circ \pm 10.5^\circ$	
$\mu_r(0)$	$21.1 \pm 0.10$ mag/arcsec <sup>2</sup>	<sup>a</sup>
$\mu_g(0)$	$21.0 \pm 0.10$ mag/arcsec <sup>2</sup>	<sup>a</sup>
$\mu_v(0)$	$21.2 \pm 0.15$ mag/arcsec <sup>2</sup>	<sup>a</sup>
$R_S^r$	17.4''	Sérsic scale radius
$R_S^v$	17.5''	Sérsic scale radius
$R_e^r$	41.3''	<sup>b</sup>
$\mu_r(R_e < R_e)$	$22.5 \pm 0.15$ mag/arcsec <sup>2</sup>	<sup>a, c</sup>
$r_h$	39.7''	<sup>d</sup>
$g_{\text{tot}}$	$13.5 \pm 0.10$	
$r_{\text{tot}}$	$13.0 \pm 0.10$	
$B_{\text{tot}}$	$13.8 \pm 0.15$	
$V_{\text{tot}}$	$13.2 \pm 0.15$	
$M_V$	$-12.4 \pm 0.20$	
$L_V$	$8.2^{+1.6}_{-1.4} \times 10^6 L_{V\odot}$	total $V$ luminosity
$V_h$	$-25 \pm 5$ km s <sup>-1</sup>	<sup>e</sup>
$V_g$	$+17$ km s <sup>-1</sup>	galactocentric velocity <sup>f</sup>
$M_{\text{stars}}$	$1.6 \pm 0.3 \times 10^7 M_\odot$	stellar mass <sup>g</sup>
$M_{\text{HI}}$	$8.7 \times 10^5 M_\odot$	gaseous mass

**Notes.** <sup>(a)</sup> Observed values, not corrected for extinction (note that the correction is smaller than the uncertainty on SB in all the passbands considered here). <sup>(b)</sup>  $R_e^r$  is the elliptical radius containing half of the galaxy light. <sup>(c)</sup>  $\mu_r(R_e < R_e)$  is the SB within the ellipse of that radius; note that this is the quantity that must be used in Fundamental Plane plots, not the SB at  $R_e$ , see Gadotti (2009). <sup>(d)</sup>  $r_h$  is the radius of the circular area containing half of the galaxy light; the same value is consistently obtained from both  $g$  and  $r$  images. <sup>(e)</sup> Mean systemic heliocentric radial velocity derived from H I observations. <sup>(f)</sup> Adopting the solar motion from Schönrich, Binney & Dehnen (2010) and  $V_{\text{rot}} = 220$  km s<sup>-1</sup>. <sup>(g)</sup> Adopting  $\frac{M}{L_V} = 2.0$ . B and V magnitudes have been obtained from their  $g$  and  $r$  counterparts using Eqs. (4) and (3).

### 3. Stellar content and distance

#### 3.1. The color magnitude diagram

The total CMDs of f2 and f1 are compared in the upper panels of Fig. 5. Our new photometry reaches  $r = 26.5$ , a full 2 mag deeper than that of K08. The RGB of VV124 is the dominant feature in the f2 CMD, running from  $(g - r, r) \simeq (0.5, 26.5)$  to  $(g - r, r) \simeq (1.2, 22.5)$  and having no counterpart in f1. The comparison reveals that the prominent vertical plume lying to the blue of the RGB, around  $(g - r) = 0$ , is equally present in f1 and f2, indicating that it is not due to a population that is characteristic of VV124.

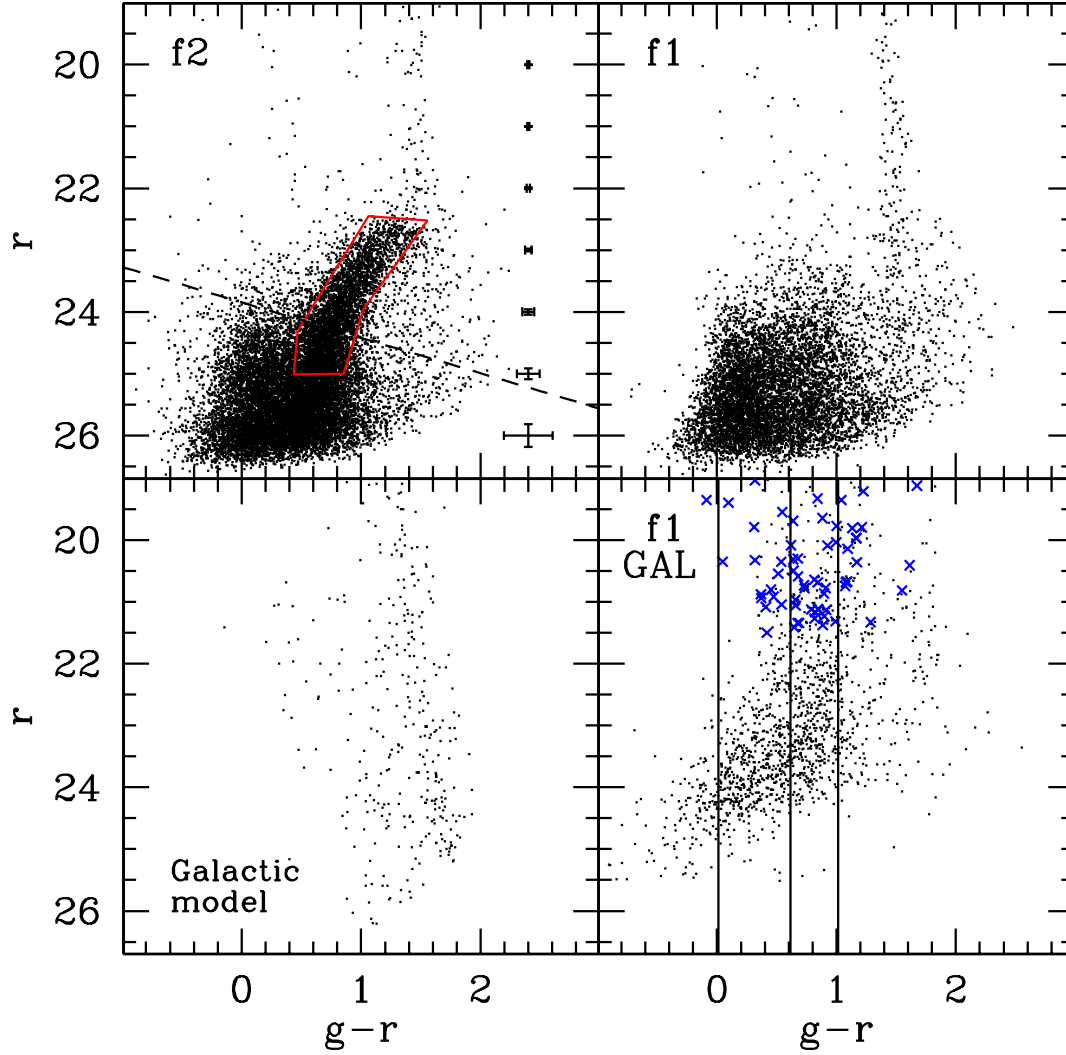
In this context, it is worthwhile interpreting the features that can be ascribed to fore/background contaminating populations which can be identified in the right panel of Fig. 5. To obtain an idea of the foreground contamination by Galactic stars, we run a simulation with the TRILEGAL Galactic model (Girardi et al. 2005). The synthetic TRILEGAL CMD for a FoV of the same area as f1 and f2 is shown in the lower left panel of Fig. 5;

the effects of photometric errors and completeness have been properly included. The model reproduces remarkably well the nearly vertical narrow plume observed in any field at  $g - r \sim 1.2$ . This is the well-known red plume of local M dwarf stars. The sparse diagonal band of stars going from  $(g - r, r) \sim (1.1, 26.0)$  to  $(g - r, r) \sim (0.2, 19.0)$  is made of Main Sequence (MS) stars lying at different distances in the Galactic halo. Also this sequence is clearly identified in the CMDs of f1 and f2, for  $r \lesssim 23.0$ , where it is not hidden by other populations. The feature may appear as remarkably narrow and well defined in the f2 CMD, but a simple inspection of the spatial distribution of the involved stars reveals they are clearly not correlated with VV124, confirming their Galactic origin.

The above discussion unavoidably leads to the conclusion that for  $r \gtrsim 23.5$  and  $g - r \lesssim 1.2$  the contaminating population is completely dominated by distant galaxies. This is a well known characteristic of deep photometric surveys (see, for example Ibata et al. 2007, their Fig. 6, in particular). This interpretation is strongly supported by the CMD of the GAL sample, shown in the lower right panel of Fig. 5: all the f1 sources plotted here have been classified as galaxies by SExtractor (small dots) or by the SDSS pipeline ( $\times$  symbols). They form two broad sequences in color matching very well the ranges spanned by the well-known red and blue sequences of galaxies (see Blanton & Moustakas 2009, for references and discussion).

A minor population of young Main Sequence / Blue Loop stars is very likely hidden in the strong background contamination, in this region of the CMD, since we see the bluest stars of this population emerging from the blob of contaminating galaxies at  $g - r \leq -0.3$  (see also J10). K08 identified a small population of bright MS stars as young as a few tens of Myr, displaying an asymmetric distribution with respect to the smoothly elliptical shape of the overall galaxy (see Fig. 1). In particular, they found that the brightest blue stars and one H II region are confined into a relatively narrow sheet in the southern half of the central 30'' of the galaxy. Most of the  $g - r \leq -0.3$  stars detected here in f2 are fainter than  $I \sim 24$ , thus they were out of reach of the K08 photometry. Figure 6 suggests that they are likely the faint counterpart of the bright blue stars discussed by K08: it is clear that they are associated with VV124 and the majority of them are confined in to the same strip located  $\sim 10$ – $20''$  to the South of the galaxy center. We used the synthetic CMD technique (see Cignoni & Tosi 2010, for references) to reproduce the observed number of these young stars (limiting the analysis to  $r \leq 25.0$ ), with the main aim of obtaining a rough estimate of the star formation rate (SFR) at recent epochs. The total mass of stars with age  $\leq 500$  Myr is  $\sim 1.4 \times 10^5 M_\odot$ , assuming a Salpeter Initial Mass Function and a metallicity  $Z = 0.001$ , i.e.  $\sim \frac{1}{100}$  of the total stellar mass of the galaxy (see Table 1). The resulting average  $SFR \sim 0.0003 M_\odot \text{ yr}^{-1}$  is in reasonable agreement with that obtained by James et al. (2004) from the integrated  $H_\alpha$  flux, once rescaled to the correct distance of VV124 (1.3 Mpc instead of 10.5 Mpc), i.e.  $SFR = 0.00008 M_\odot \text{ yr}^{-1}$ , given the considerable uncertainties involved. The agreement is good also with the SFH derived by J10 in the same age bin.

While the presence of these stars and their asymmetric distribution indicate recent activity in the galaxy (possibly connected to the asymmetric structure of the H I density and velocity field, see Sect. 5), the associated star formation episode produced only a minor component of the overall stellar mix populating VV124. This young population is more abundant in the innermost region of the galaxy and is best characterized with the HST photometry by J10, who concluded that it is quite rare at distances larger than 40'' from the center and that it formed in the last 500 Myr. The



**Fig. 5.** *Upper panels:* CMDs of the entire Chip 2 (left) and Chip 1 (right) fields. The dashed line marks the limiting magnitude reached in the  $V, I$  photometry by K08. The average  $r, g-r$  uncertainties are plotted as errorbars. The comparison between the two panels reveals the steep and wide RGB of VV124, tipping at  $r \approx 22.5$ , that dominates the f2 CMD while is completely lacking in the f1 one. The red polygon enclosing the RGB of VV124 is used to select stars for the star counts described in Sect. 4. *Lower left panel:* predictions of the TRILEGAL Galactic model (Girardi et al. 2005) for a field of the same area as f1 and f2 in the direction of VV124. The model includes *only* Galactic stars. The effects of photometric uncertainties have been properly added. *Lower right panel:* CMD of the sources classified as *galaxies* by SExtractor in f1 (small dots). The blue  $\times$  symbols are the sources brighter than  $r = 20.5$  classified as *galaxies* in the SDSS catalogue in the same area. The vertical lines approximately enclose the color range spanned by *Red* and *Blue* Sequence galaxies, according to Blanton & Moustakas (2009); see also Balogh et al. (2009).

same is true for the *very* sparse population of candidate AGB stars brighter than the tip. For these reasons, in the following we will focus mainly on the RGB stars that are the visible part of the old stellar population which seems to dominate the galaxy.

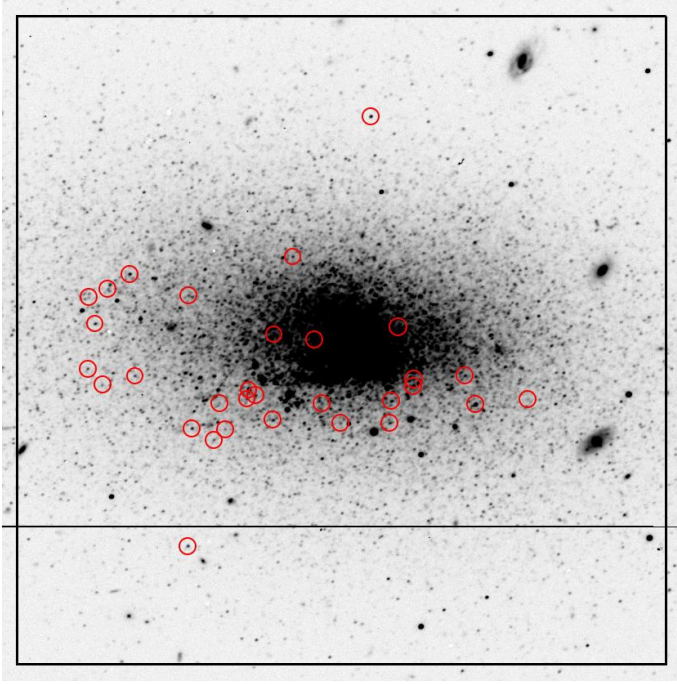
### 3.2. Distance from the tip of the RGB

The tip of the red giant branch (TRGB; Lee et al. 1993) is widely recognized as one of the most straightforward and general applicable distance indicators (see Bellazzini 2008, B08 hereafter, for references and discussion). In the present case, it is also the only standard candle accessible with our data to estimate the distance of VV124. Figure 7 shows the very clean detection of the TRGB of VV124 we obtained from our data: the tip is unequivocally detected by the Sobel filter (see Lee et al. 1993, B08) as an obvious cut-off in the luminosity function (LF) of the RGB at  $r_0^{\text{TRGB}} = 22.61 \pm 0.06$ , where the reported

uncertainty is the half width at half maximum (HWHM) of the highest peak in the filter response (lower right panel of Fig. 7). It is interesting to note that the uncertainty of the TRGB position is a factor of 2 lower than reported in T10, owing to the much higher resolution/accuracy of our own photometry. The average color of the RGB at the tip is  $(g-r)_0 = 1.28 \pm 0.02$ .

While an empirical calibration of the absolute magnitude of the TRGB in the SDSS passbands is still lacking, in B08 and Bellazzini (2009) it has been shown that all available theoretical models agree in predicting a very modest dependency of  $M_r^{\text{TRGB}}$ ,  $M_i^{\text{TRGB}}$ , and  $M_z^{\text{TRGB}}$  on metallicity and age, at least for relatively metal-poor models ( $[\text{Fe}/\text{H}] \leq -0.7$ ; this is also the main reason which makes  $M_i^{\text{TRGB}}$  so appealing as a standard candle, B08). In particular, considering Girardi et al. (2004) models of age = 12 Gyr and 4 Gyr and spanning the full range of available metallicity, we found that for TRGB colors  $(g-r)_0 \leq 1.4$  the average magnitude of the tip is  $M_r^{\text{TRGB}} = -3.03$  with a standard





**Fig. 6.** Sources having  $r < 25.0$  and  $g - r \leq -0.3$  are overplotted (red open circles) on a LBC  $g$  image of VV124 zoomed on the center of the galaxy. The main body of the galaxy is enclosed within a square of side  $l = 3'$ . The orientation is the same as in Fig. 1.

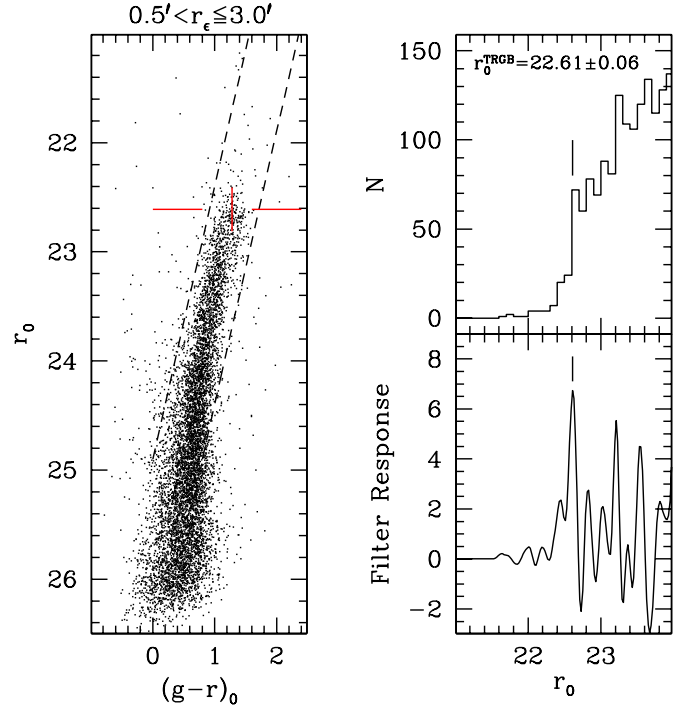
deviation of just 0.04 mag. This is in excellent agreement with the predictions of the independent set of isochrones by Dotter et al. (2008, see B08 for some example in other passbands). The low scatter in  $M_r^{\text{TRGB}}$  in the considered range of age and colors is confirmed also by BASTI (Pietrinferni et al. 2004) models, but in this case the average magnitude of the tip is  $\approx 0.08$  mag brighter than in other models (see Bellazzini 2009). The latter difference is still within the uncertainty in the absolute zero point of the calibration (see Bellazzini et al. 2004a, B08 and references therein). Adopting  $M_r^{\text{TRGB}} = -3.03 \pm 0.04$ ,  $r_0^{\text{TRGB}} = 22.61 \pm 0.06$  and including an uncertainty of 0.1 mag for the overall zero point we obtain  $(m - M)_0 = 25.61 \pm 0.13$ ; taking BASTI models we would have obtained  $(m - M)_0 = 25.72$ , instead.

Another route to estimate the distance from the tip is to convert the observed magnitude and colors from  $r_0, (g - r)_0$  to  $I_0, (V - I)_0$  using the relations reported in Sect. 2 and then to adopt the empirical calibration:

$$M_I^{\text{TRGB}} = 0.080(V - I)_0^2 - 0.194(V - I)_0 - 3.939 \pm 0.12 \quad (7)$$

derived by B08 from the original calibration as a function of  $[\text{Fe}/\text{H}]$  obtained in Bellazzini et al. (2001) and revised in Bellazzini et al. (2004a). We obtain  $(V - I)_0^{\text{TRGB}} = 0.981 \pm 0.06$  and, in turn,  $M_I^{\text{TRGB}} = -4.05 \pm 0.12$ , that coupled with  $I_0^{\text{TRGB}} = 21.53 \pm 0.10$  gives  $(m - M)_0 = 25.58 \pm 0.16$ , fully supporting the conclusions reached above, based on the Girardi et al. (2004) and Dotter et al. (2008) models. As our final best estimate we adopt  $(m - M)_0 = 25.61 \pm 0.13$ , corresponding to  $D = 1.3 \pm 0.1$  Mpc; this value will be always adopted in the following. At this distance 1 arcmin corresponds to 378 pc.

The main reason for the marginal difference with respect to the estimate by T10 ( $D = 1.1 \pm 0.1$  Mpc) resides in the brighter



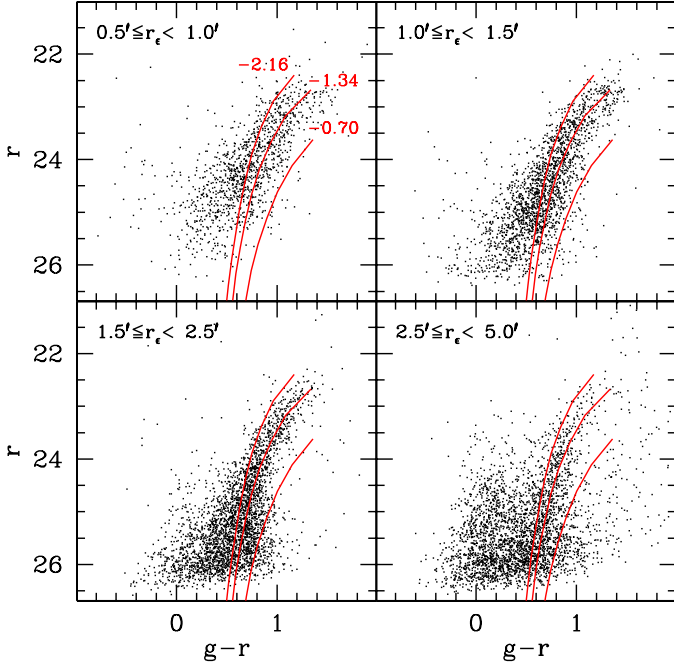
**Fig. 7.** Determination of the  $r$  magnitude of the RGB tip. *Left panel:* de-reddened CMD for the indicated elliptical annulus. The two parallel dashed lines enclose the RGB stars selected to derive the luminosity function. The pair of horizontal segments mark the level of the tip, the vertical segment marks the average color at the tip. *Upper right panel:* LF of the RGB. The sharp cut-off corresponding to the TRGB is marked by a vertical segment. *Lower right panel:* Sobel filter response as a function of  $r$  magnitude. The peak corresponding to the TRGB is marked by a vertical segment.

level of the TRGB found by T10: this may be due (a) to a larger impact of blending in their lower resolution photometry, and/or (b) to a systematic error in the absolute photometric calibration which should not affect our photometry as we have the standards in field. Further support for the larger distance estimate obtained here is provided by the excellent agreement with the estimate by J10<sup>7</sup>.

### 3.3. Metallicity

In Fig. 8 we compare the CMD of VV124 in different elliptical annuli with a grid of RGB ridge lines of Galactic globular clusters from the set by Clem et al. (2008), converted from the  $u'g'r'i'z'$  system to the  $ugriz$  one according to Tucker et al. (2006). From blue to red, the RGB templates are for: M 92, at  $[\text{Fe}/\text{H}] = -2.16$  (all the metallicities are in the scale by Carretta & Gratton 1997, CG97 hereafter), M 3 ( $[\text{Fe}/\text{H}] = -1.34$ ) and M 71 ( $[\text{Fe}/\text{H}] = -0.70$ ). The reddening and distance moduli adopted for the templates are taken from Ferraro et al. (1999). The comparison of the observed RGB with GC templates is the standard way to obtain estimates of the metallicity of an old stellar population from photometric data (see, e.g. Harris & Harris 2000; Bellazzini et al. 2005, and references therein). It is known to provide valuable constraints on the overall metallicity distribution when the considered RGB is dominated by stars with age

<sup>7</sup> J10 reports  $(m - M)_0 = 25.67 \pm 0.04$ . Note that the reported error does not account for the systematic uncertainty in the zero point of the calibration, that is of order 0.1 mag (Bellazzini et al. 2004a, B08).



**Fig. 8.** RGB fiducial ridge lines are super-imposed to the CMD of stars in four different elliptical annuli around the center of VV124. The ridge lines are labeled with the metallicity of the associated cluster (in the CG97 scale) in the upper left panel.

comparable with that of classical GCs ( $\geq 8-10$  Gyr<sup>8</sup>). The SFH derived by J10 from HST data indicates that the vast majority of VV124 stars are older than 10 Gyr even in the innermost region, thus supporting the idea that the analysis is well suited for the present case.

The first general remarks that can be made by inspecting Fig. 8 are: (a) the majority of RGB stars of VV124 are remarkably metal-poor, with  $[\text{Fe}/\text{H}] \leq -1.0$ , and (b) the observed color spread at any magnitude is significantly larger than expected from mere photometric errors, hence there should be a significant spread in metallicity (see below); both conclusions were drawn also by K08 and are confirmed by J10. The distributions of RGB stars in the four panels seem to indicate that the innermost regions host a larger fraction of relatively metal-rich stars compared to the external ones, in agreement with the typical metallicity gradient observed in dSphs (Harbeck et al. 2001). It may be hypothesized that the larger number of RGB redder than the M3 ridge line in the innermost annulus is due to a larger fraction of blending in this most crowded region (see Fig. 3). However, this cannot be the case, as blending spuriously increase the luminosity of stars, thus mimicking bluer colors and lower metallicities, not higher. On the other hand, higher crowding also implies larger photometric errors and, consequently, broader color distributions in the inner regions. Tests performed using synthetic stars from our set of artificial stars experiments suggests that it is very unlikely that the observed changes of the color distribution of RGB stars with radius is due to mere observational effects.

We obtained a rough estimate of the metallicity of each star by linear interpolation on the grid of ridge lines of Fig. 8, as done, for example, in Harris & Harris (2000), Saviane et al. (2000), and Bellazzini et al. (2003). To limit any kind of

contamination as well as the impact of photometric uncertainties we considered only the stars having  $22.7 \leq r < 24.0$  and enclosed between the ridge lines of M92 and M71. The average metallicity and the standard deviation in the outermost radial bin considered in Fig. 8, i.e. the one less affected by crowding and photometric errors, are  $\langle [\text{Fe}/\text{H}] \rangle = -1.5$  (which we adopt as the typical metallicity of the galaxy, in the following) and  $\sigma_{[\text{Fe}/\text{H}]}^{\text{obs}} = 0.34$  dex. Once de-convolved from the dispersion due to observational effects ( $\sigma_{[\text{Fe}/\text{H}]}^{\text{synth}} = 0.13$  dex, estimated from artificial stars), this leads to an intrinsic one-sigma metallicity spread of  $\sim 0.3$  dex, typical of dSph galaxies (Mateo 1998; Tolstoy et al. 2009).

### 3.3.1. An extended horizontal branch?

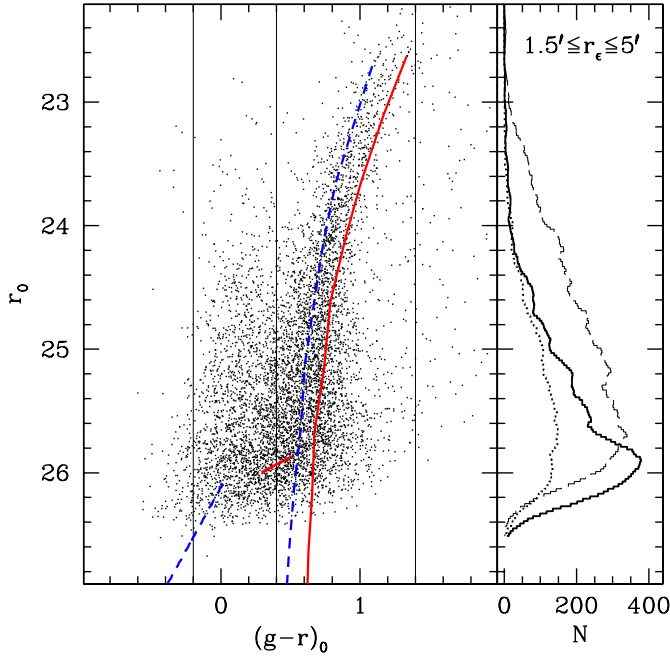
J10 clearly detect an RC (and an old red HB) approximately peaking at a magnitude corresponding to our  $r_0 \sim 26.5$ ; they attribute part of this population to stars with age between 0.5 and 1 Gyr. However, this is only a minor component of their SFH, hence the majority of the core-He-burning stars they observe must be associated with the dominant old population. We do not see any sign of an RC population, even in the less-crowded outer regions of VV124 ( $r_\epsilon \geq 1.5'$ ). The LF of the stars in the color range expected to enclose such a feature is shown as a long-dashed thin line in the right panel of Fig. 9 and it shows no hint of the characteristic peak due to an RC population (compare, for example, with the case of Leo I, which hosts a significant intermediate-age population, Bellazzini et al. 2004b; Smolčić et al. 2007). This is likely due to the sudden drop of completeness occurring in our sample in this magnitude range, although radial age/metallicity gradients may also play a role. Probably the RC is less conspicuous in the outer regions of VV124, if they are populated by older and more metal-poor stars than those inhabiting the center, on average.

Along these lines, it is suggestive to note, in Fig. 9, that the HB ridge lines of the Galactic globular clusters NGC 2419 ( $[\text{Fe}/\text{H}] = -2.1$ , Harris 1996; distance and reddening from Ripepi et al. 2007) and Pal4 ( $[\text{Fe}/\text{H}] = -1.4$ , Koch & Côté 2010; distance and reddening from Harris 1996), nicely fall on top an over-density that has no counterpart in the CMD of the control field (f1). This is clearly shown in the right panel of Fig. 9 where the LF of VV124 stars in the color range  $-0.2 < (g-r)_0 \leq 0.4$  is compared with stars in the same range from a field of equal area from f1. While the LF of the control field rise gently up to  $r \sim 26$  where it drops down to the limiting magnitude, the LF of the considered annulus around VV124 shows a sharp rise of star counts at  $r \simeq 25.6$ , peaking at  $r \simeq 25.9$ .

We tentatively interpret this feature as an extended old HB population associated with VV124. If this interpretation is correct, the galaxy must host a sizable population of RR Lyrae: unfortunately, the entire set of observations used in this paper was acquired in less than one hour, making it impossible to search for candidate variable stars. It must be recalled that all the results presented in this sub-section concern stars within one magnitude from the limit of our photometry, i.e. a realm where the completeness is rapidly dropping and the photometric errors are quite large. Yet we feel that they are worth to be reported, in the hope they may trigger further investigations.

<sup>8</sup> See [www.lorentcenter.nl/lc/2009/324/friday/Bellazzini.ppt](http://www.lorentcenter.nl/lc/2009/324/friday/Bellazzini.ppt) for some recent tests on the reliability of the technique.

<sup>9</sup> All the results presented in this section are unchanged if completeness-corrected LFs are considered instead of the uncorrected ones shown in Fig. 9.

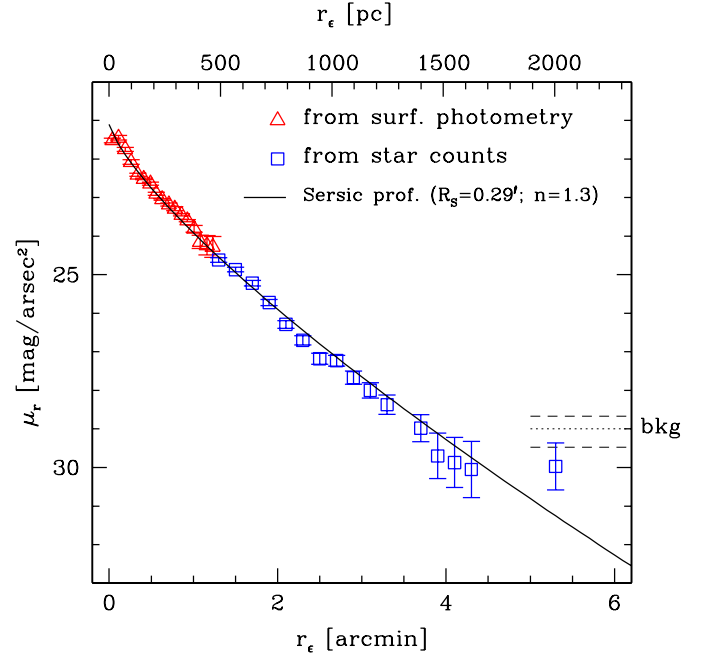


**Fig. 9.** *Left panel:* de-reddened CMD of the stars lying in the elliptical annulus  $1.5' \leq r_\epsilon \leq 5.0'$ , with the (RGB and HB) ridge lines of the GCs NGC 2419 (dashed blue line) and Pal4 (continuous red line), de-reddened and shifted to the distance of VV124, as derived here. The ridge lines have been derived by us from public SDSS data. The thin vertical lines enclose the typical color range of HB ( $-0.2 < (g-r)_0 \leq 0.4$ ) and RGB ( $-0.4 < (g-r)_0 \leq 1.4$ ) stars; the latter range is expected to enclose also the Red Clump of an intermediate-age population. *Right panel:* the LF of the stars in the HB color range in the considered annulus (thick continuous line) is compared to the LF in the same color range from an equivalent area of f1 (dotted line). The thin long-dashed line is the LF of the stars in the RGB color range.

#### 4. Structure

In Fig. 10 we show the azimuthally-averaged major-axis r-band surface brightness (SB) profile of VV124. The profile has been obtained by joining the surface photometry on concentric elliptical apertures obtained with Xvista out to  $r_\epsilon = 72'' \approx 1.2'$  (see Sect. 2.4), with the surface density profile obtained from star counts in  $r_\epsilon^{10}$ , which are equivalent to star counts on elliptical annuli (see Federici et al. 2007, for a discussion of the procedure and details). For star counts we used likely VV124 members selecting candidate RGB stars enclosed in the polygonal box shown in the upper left panel of Fig. 5. Star counts are limited to the largest ellipse (with the parameters reported in Sect. 2.4) which is completely enclosed within f2, i.e. only to RGB stars having  $r_\epsilon \leq 6.0'$ . The two profiles overlap with two points in the region between  $\approx 1'$  and  $\approx 1.2'$ : the overlap region was used to normalize the star counts profile, shifting it to the same scale of SB of the surface photometry profile<sup>11</sup>. The SB values (not corrected for extinction) as a function of  $r_\epsilon$  are listed in Table 2.

Surface brightness profiles of VV124 were previously obtained (in several passbands) by Jansen et al. (2004a) and by



**Fig. 10.** Surface brightness profile of VV124 in r band obtained by joining surface photometry (for  $r_\epsilon \leq 72''$ ; Sect. 2.4) and star counts (for  $r_\epsilon > 72''$ ) profiles. The continuous line is the Sérsic model that best-fits the surface photometry. The level of the background (bkg, dotted line) and the associated uncertainty (dashed lines) are also reported. The error bars from surface photometry are typically smaller than the dimension of the points.

Taylor et al. (2005), from surface photometry limited to  $r_\epsilon \leq 1.5'$ . Once transformed to the proper photometric band (using Eqs. (3) and (4)), both profiles are in good agreement with ours in the overlapping region. The novelty of Fig. 10 is that using star counts in the outer regions we were able, for the first time, to trace the SB profile out to  $\approx 5' \approx 1.9$  kpc, reaching  $\mu_r \approx 30.0$  mag/arcsec<sup>2</sup>, thus demonstrating that the galaxy is much more extended than previously believed. It is interesting to note that a Sérsic (1968) model of scale-length  $R_s = 0.29' = 110$  pc and  $n = 1.3$  (i.e., a nearly exponential profile, in agreement with T10) provides a good fit to the observed profile over the whole considered range  $0.0' \leq r_\epsilon \leq 5.0'$ .

The main structural parameters we obtained from the observed profile are listed in Tab. 1. To estimate the integrated magnitude, we computed the total flux within the maximum elliptical aperture we reach with surface photometry ( $r_\epsilon = 72''$ ); next we used the best-fit Sérsic model to find the fraction of light outside that radius. It turned out that a correction of  $-0.1$  mag should be applied to the magnitude within  $r_\epsilon = 72''$  to account for the contribution of these external regions. By transforming our integrated  $g$  and  $r$  magnitudes into an integrated  $B$  magnitude (with Eq. (4)) we obtain  $B_{\text{tot}} = 13.8 \pm 0.25$  in good agreement with previous estimates from Taylor et al. (2005, reported also by K08) and Jansen et al. (2004a),  $B_{\text{tot}} \approx 13.7$ . The absolute  $V$  magnitude is  $M_V = -12.4$ , corresponding to  $L_V = 8.2 \times 10^6 L_{V,\odot}$ .

##### 4.1. Density maps

The two dimensional density maps shown in Fig. 11 are even more interesting than the extended profile shown above. Both maps are obtained by estimating the density from star counts on a fixed regular grid of nodes spaced by  $0.2'$  in both directions,

<sup>10</sup> I.e., keeping fixed the values of  $\epsilon$  and PA derived in Sect. 2.4.

<sup>11</sup> For  $r_\epsilon \leq 1'$  the star counts profile is strongly affected by radial variations in the completeness factor. The surface photometry profile was transformed onto the standard scale of  $g, r$  magnitudes using Eqs. (1) and (2).



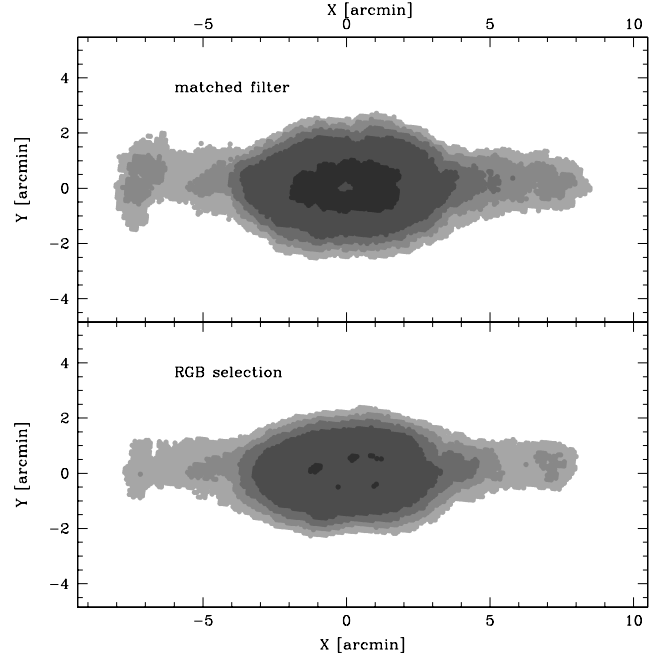
**Table 2.** Observed surface brightness profiles of VV124.

$r_\epsilon$ arcmin	$\mu_r$ mag/arcsec <sup>2</sup>	$\mu_g$ mag/arcsec <sup>2</sup>	source
0.04	21.52 ± 0.06	21.40 ± 0.02	sp
0.11	21.45 ± 0.06	21.75 ± 0.07	sp
0.19	21.75 ± 0.05	21.94 ± 0.05	sp
0.26	22.08 ± 0.06	22.30 ± 0.06	sp
0.34	22.41 ± 0.04	22.59 ± 0.06	sp
0.41	22.52 ± 0.02	22.67 ± 0.06	sp
0.49	22.64 ± 0.04	22.96 ± 0.05	sp
0.56	22.90 ± 0.04	23.18 ± 0.04	sp
0.63	23.05 ± 0.02	23.48 ± 0.04	sp
0.71	23.18 ± 0.04	23.94 ± 0.05	sp
0.78	23.29 ± 0.05	23.99 ± 0.04	sp
0.86	23.45 ± 0.03	24.06 ± 0.03	sp
0.93	23.60 ± 0.03	24.12 ± 0.03	sp
1.01	23.81 ± 0.09	24.17 ± 0.03	sp
1.08	24.15 ± 0.17	24.34 ± 0.02	sp
1.16	24.24 ± 0.25	24.54 ± 0.02	sp
1.23	24.28 ± 0.27	24.79 ± 0.02	sp
1.30	24.62 ± 0.06	24.92 ± 0.06	sc
1.50	24.87 ± 0.06	25.17 ± 0.06	sc
1.70	25.22 ± 0.07	25.52 ± 0.07	sc
1.90	25.72 ± 0.08	26.02 ± 0.08	sc
2.10	26.29 ± 0.10	26.59 ± 0.10	sc
2.30	26.70 ± 0.12	27.00 ± 0.12	sc
2.50	27.18 ± 0.14	27.48 ± 0.14	sc
2.70	27.23 ± 0.14	27.53 ± 0.14	sc
2.90	27.67 ± 0.17	27.97 ± 0.17	sc
3.10	28.00 ± 0.20	28.30 ± 0.20	sc
3.30	28.37 ± 0.25	28.67 ± 0.25	sc
3.70	28.98 ± 0.35	29.28 ± 0.35	sc
3.90	29.70 ± 0.59	30.00 ± 0.59	sc
4.10	29.87 ± 0.65	30.17 ± 0.65	sc
4.30	30.05 ± 0.73	30.35 ± 0.73	sc
5.30	29.97 ± 0.61	30.27 ± 0.61	sc

**Notes.** sp = surface photometry; sc = star counts.

with an adaptive algorithm that adjusts the spatial resolution according to the local density. To describe the algorithm, it is more convenient to refer to the map in the lower panel of Fig. 11. In this case, likely RGB stars of VV124 are selected by requiring they lie within the selection box plotted in Fig. 12, similarly to what was done for the SB profile. Next, for each node of the grid we find the distance  $D_{50}$  of the 50th star in order of distance from the node itself. Following this, the local density (in stars/arcmin<sup>2</sup>) is computed by dividing 50 by the area of the circle of radius  $D_{50}$  (see Silverman 1986; Bellazzini et al. 2002b, for discussion and another application of the same concept). The average density of the background, computed using the same selection over the whole f1, is then subtracted to this number and the total 1- $\sigma$  error of the background-subtracted density is computed, assuming Poisson statistics. In the maps of Fig. 11 the density is expressed in units of  $\sigma$  above the background.

The map in the upper panel has been obtained in the same way, but adopting the matched filter (MF) scheme (Rockosi et al. 2002) instead of a selection box. At each grid node the density is computed by summing the *weights* of the 50 stars within  $D_{50}$ ; the weights are assigned according to the star position in the CMD within the weight pattern shown in greyscale in Fig. 12. The weights are obtained as a map of ratios of the number of stars from f2 to the number of stars from f1 in a given position on the CMD, normalized to have the maximum equal to unity. It

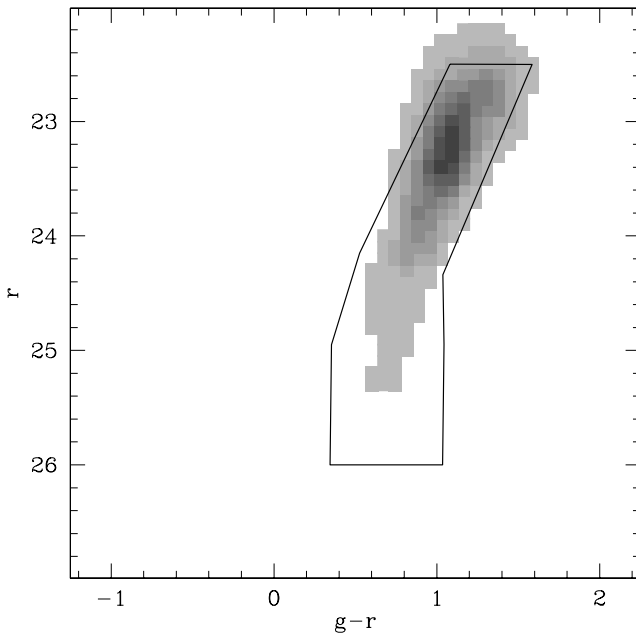


**Fig. 11.** Upper panel: density map obtained with the *matched filter* (MF) technique, adopting the pattern of weights shown in greyscale in Fig. 12. Lower panel: density map obtained using RGB stars selected to lie within the box shown in Fig. 12. The levels of grey range between  $3\sigma$  to  $8\sigma$  above the background, in steps of  $1\sigma$ , from the lightest to the darkest tone of grey. The density depressions near the center of the main body are due to the low degree of completeness in the very crowded innermost  $r_\epsilon \leq 0.5'$  region.

is clear from Fig. 12 that the MF approach is more conservative, as the bulk of the signal is provided by the most likely genuine VV124 RGB members, most of the weight being assigned to stars brighter than  $r = 24.5$ . This is the reason the associated density map is less smooth than the one derived from the selection box, which equally weights all the candidate RGB stars down to  $r = 26.0$ . In any case, we want to stress that we have obtained density maps using various adaptive and non-adaptive (fixed radius) density estimators and *in all cases we obtained density distributions with the same features shown in Fig. 11*.

The most striking features of the density maps are two symmetric, relatively thin wings emanating from the edges of the elliptical (bulge-like<sup>12</sup>) main body around  $X \gtrsim 3'$  and reaching  $X \simeq 8'$ , approximately aligned along the major axis of the galaxy. These structures have no obvious counterpart in the other dwarf galaxies of the Local Group. The overall density distribution recalls a disk galaxy with a prominent bulge, seen nearly edge-on. The galaxy is quite gas-poor as a whole and no hint of H I is observed in the wings (see Sect. 5). Hence, the wings would be interpreted as the dry remnant of an ancient disk that evolved undisturbed until the total consumption of the original gas it was made of. In this context, it is interesting to recall that T10 interpret the structure of VV124 as a superposition of disks of different thickness, the thickest being populated by old RGB stars, the thinnest by young Main Sequence and Red Super Giants. Alternatively, the wings may be identified with the inner regions of two tidal tails (see Muñoz et al. 2008; Klimontowski et al. 2009, and references therein), but this explanation seems

<sup>12</sup> Or *pseudo-bulge-like* (see, e.g., Gadotti 2009, and references therein).

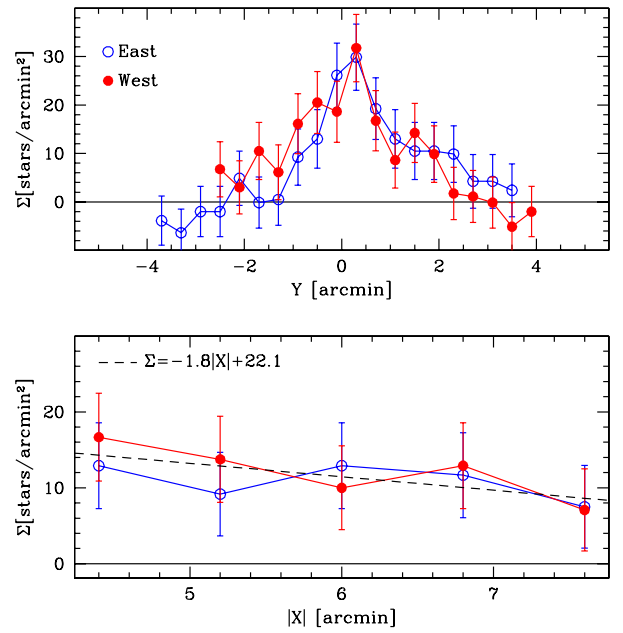


**Fig. 12.** Selection box (continuous line) and weight pattern (in greyscale) adopted for the density maps shown in Fig. 11. Higher weights corresponds to darker grey areas, going from 0.1 (lightest grey) to 1.0 (darkest grey), with step 0.1. Weight = 0.0 is assigned to stars outside the grey area, hence these stars do not contribute to the density estimate.

unlikely, given the extreme isolation of VV124 from any other mass distribution (both the MW and M 31 are  $\approx 1.3$  Mpc away, and the nearest dwarf is Leo A, at a distance of  $\approx 700$  kpc; see J10).

To further check the significance of these very unusual structures, as well as their actual association to VV124, we obtained the surface density profiles of the two wings along the  $X$  and  $Y$  directions, using stars selected to lie within the RGB box shown in Fig. 12. In both cases, the background has been estimated from f1, adopting the same selections and procedures, and subtracted to the f2 profiles. Since the major axis of the galaxy is inclined by just  $5.8^\circ$  with respect to the E-W direction, in the following we will refer to the wing at positive  $X$  as to the Western wing and to that at negative  $X$  as to the Eastern wing. In Fig. 13 the  $Y$  (upper panel) and  $|X|$  (lower panel) profiles of the Eastern and Western wings are compared. There are several conclusions that can be drawn from these plots:

- The over-density in the considered regions is clear and significant in both profiles and in both wings.
- The profiles of the E and W wings are indistinguishable, both in the  $Y$  and in the  $|X|$  direction. Both  $Y$  profiles have a clear peak near  $Y = 0$ , i.e. at main the plane of symmetry of the whole galaxy.
- We do not see any obvious truncation of the wings in the  $X$  direction, but it is hard to draw any conclusion on this, given the very low surface brightness of the considered structures. Extrapolating the linear fit to the observed profiles (dashed line),  $\Sigma = 0$  is reached at  $|X| \sim 12'$ . Note that the fit is not intended to bear any physical meaning, it was attempted just to perform the above extrapolation to zero surface density.



**Fig. 13.** Background-subtracted surface density profiles of the Eastern (blue open circles) and Western (red filled circles) wings of the density distribution shown in Fig. 11, from counts of RGB stars selected with the same box used for the density maps (see Fig. 12). *Upper panel:* profiles along the  $Y$  direction. *Lower panel:* profiles along the  $|X|$  direction; the adoption of the absolute value of  $X$  allows to compare the Eastern to the Western wing in the same scale. The dashed line is the best linear fit to the distribution of points from both wings. In all the cases only stars within  $|Y| \leq 1.5'$  and  $4' \leq |X| \leq 8'$  have been considered.

From the results described above it can be concluded that the wings are clearly associated to VV124, as it is very hard to conceive how any kind of unrelated structure in the background can present such a degree of symmetry in the Western and Eastern sides of the galaxy, as well as such a degree of correlation with the major axis of the galaxy.

From this analysis it is not possible to draw firm conclusions on the actual nature of the wings. However, it should be noted that the strong peaks at  $Y = 0$  shown by the density profiles in the  $Y$  direction seems more typical of a disk than of a tidal stream. The kinematics of stars in the whole galaxy *and* in the wings will certainly provide very useful insight into the origin of the wings, e.g., by looking for the signature of coherent rotation about the minor axis (see, for example, the case of the isolated Tucana and Cetus dSph [Fraternali et al. 2009](#); [Lewis et al. 2007](#), respectively).

To obtain further insight into the possible tidal origin of the wings, we performed simple plausibility tests by comparing the observed size of VV124 to its expected tidal radius for two basic scenarios, described below. The tidal radius  $r_t$  is defined as the cut-off radius in the density distribution of a system of mass  $m$  imposed by the tides from a mass  $M$  lying at distance  $D$ . In this case we will use the formula

$$r_t = \frac{2}{3} \left( \frac{m}{2M} \right)^{\frac{1}{3}} D \quad (8)$$

which is appropriate for a logarithmic potential (see [Bellazzini 2004](#), for discussion and references).

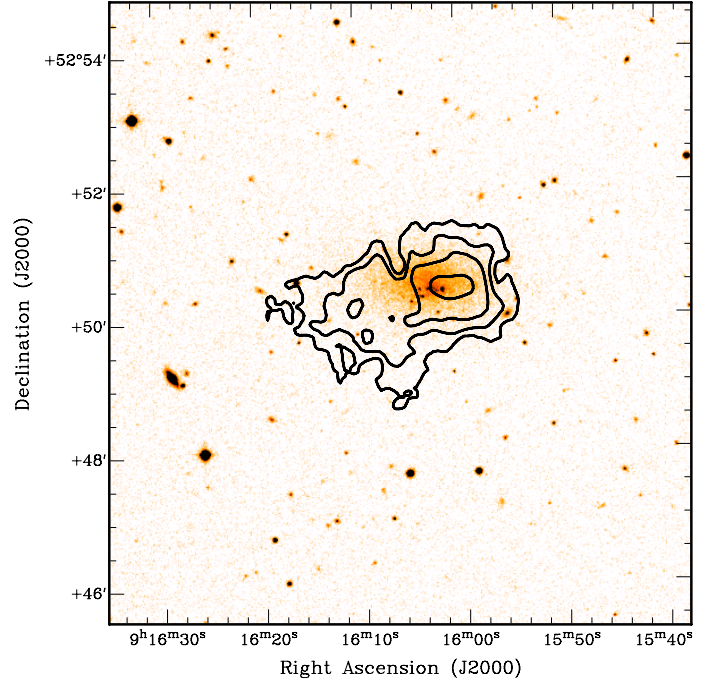
1. Let us consider the tidal force exerted on VV124 by the Local Group as a whole, as if the LG was a single giant galaxy whose center is located at the barycenter of the LG, adopted to lie at  $D = 1.2$  Mpc from VV124 (van den Bergh 2000). This is clearly too simple a model for the mass distribution of the LG, but it may provide a rough upper limit to the tidal force that may be felt by VV124. Taking the stellar mass listed in Tab. 1 as the total mass of VV124 (a conservative choice, in this context) we find that for the range spanned by the most recent estimates of the LG mass ( $2\text{--}6 \times 10^{12} M_{\odot}$ , see van der Marel & Guhathakurta 2008, and references therein) the expected tidal radius ranges between 8 kpc and 13 kpc. This is significantly larger than the maximum size of the main body of VV124 ( $r_{\epsilon} \simeq 2$  kpc), and also larger than the size of the wings themselves, which reach  $r_{\epsilon} \simeq 3$  kpc. Hence, it seems unlikely that the structure of VV124 could have been shaped by the tidal interaction with the LG as a whole or by one of its major components, as both the MW and M 31 are more distant and less massive than the ideal super-galaxy considered here.
2. We now test the case of a close interaction with a dwarf galaxy. In the hierarchical paradigm, the accretion of small groups of dwarf galaxies by a major halo should not be uncommon (see D'Onghia et al. 2009, and references therein), thus such a scenario is not unlikely, in principle. We consider the nearest dwarf to VV124, i.e. Leo A, a dIrr galaxy with mass  $M \simeq 8 \times 10^7 M_{\odot}$  (Brown et al. 2007). Solving Eq. (8) for  $D$ , we found that for Leo A to impose a tidal radius as small as 3 kpc to VV124, the two dwarfs should have been as close as  $\sim 10$  kpc in the past. It is likely that from such a close encounter the two galaxies should have emerged either as a bound pair or with high peculiar velocities (Sales et al. 2007), none of which is currently observed.

To follow up on these simple considerations, we plan to search for isolated dwarfs showing signs of tidal interactions in recent simulations of the evolution of LG-size groups, performed in a realistic cosmological context. However, this is clearly beyond the scope of the present paper.

## 5. Neutral hydrogen

In order to study the possible presence of neutral hydrogen in VV124, the galaxy was observed with the WSRT on April 13, 2008. A bandwidth of 10 MHz (corresponding to  $\sim 2000 \text{ km s}^{-1}$ ) was used which was covered by 2048 channels, resulting in a velocity resolution of about  $2 \text{ km s}^{-1}$  after Hanning smoothing the spectra. The integration time was 12 h. Calibration and analysis of the data were done following standard WSRT recipes using *MIRIAD* software (Sault et al. 1995). Several datacubes were made by varying weighting and tapering. Lower resolution cubes, which, in principle, are more sensitive to faint, extended emission, do not show more H I compared to the full resolution datacube. The spatial resolution of this datacube is  $13 \times 16$  arcseconds and the noise level is  $1.2 \text{ mJy beam}^{-1}$ . The faintest detected emission is at the level of  $5 \times 10^{19} \text{ cm}^{-2}$ .

Neutral hydrogen was clearly detected in VV124. Figure 14 shows the distribution of H I in relation to the optical galaxy. The total H I image was derived by smoothing the full-resolution data to 30 arcsec resolution and clipping this smoothed datacube at  $3\sigma$  to make a mask which was applied to the full resolution datacube. The H I is fairly well centered on VV124, with the peak of the emission about 1 arcmin W of the center. To the



**Fig. 14.** Total H I contours on top of an optical image (with image cuts putting in evidence only the densest central part of the stellar body of the galaxy). Contour levels are 5, 10, 20 and  $50 \times 10^{19} \text{ cm}^{-2}$ .

SE the H I extends to larger radius and seems to form a tail-like structure.

The flux integral of the H I emission is  $2.2 \pm 0.1 \text{ Jy km s}^{-1}$  which, for a distance of 1.3 Mpc, gives a total H I mass of  $8.7 \pm 0.4 \times 10^5 M_{\odot}$ . Given the optical luminosity of VV124, this implies that, although this galaxy contains a significant amount of H I, it is relatively gas poor. In a study of Local Group dwarf galaxies, Grcevich & Putman (2009) find that Local Group dwarfs that are, like VV124, about 1 Mpc distant from the Milky Way and Andromeda typically have  $M_{\text{HI}}/L_V \simeq 1$ , while for VV124  $M_{\text{HI}}/L_V = 0.11$ . Only the Cetus and Tucana dwarfs are more gas poor (with  $M_{\text{HI}}/L_V$  below 0.01).

In Fig. 15 we show the velocity field of the H I emission. This velocity field was derived using the intensity weighted mean of the masked cube that was also used for deriving the total H I emission. The kinematics of the H I does not show any signature of overall rotation over the optical body of VV124. Such kinematics is seen in most dwarfs with a dynamical mass below  $10^8 M_{\odot}$  (Begum et al. 2008). The systemic velocity of the H I coinciding with the optical body is  $V_h = -25 \pm 4 \text{ km s}^{-1}$ , quite different from  $V_h \simeq -70 \text{ km s}^{-1}$  reported by K08; a detailed comparison between the H I velocity field and the results from optical spectroscopy is reported in Sect. 5.1. The tail-like extension to the SE seems to have a velocity gradient towards more negative velocities.

The origin of this H I tail is not clear. A possibility would be that the gas is displaced from the main body by the combined action of stellar winds. The small gradient in velocity ( $5\text{--}10 \text{ km s}^{-1}$ ) and the small mass of gas in the tail ( $\simeq 10^5 M_{\odot}$ ) would require a kinetic energy of  $\sim 10^{51} \text{ erg}$ , at most. Such an energy can be provided by about 10 OB stars within a few million years with an efficiency of transferring kinetic energy to the ISM of 10%. However, if the H I tail is caused by a galactic wind, the latter should be highly asymmetric given that the tail is seen only on one side and also there are no signs of double peaks in



the line profiles that could point to an expanding shell. A second possibility is that of ram pressure stripping. This would justify the head-tail morphology of the HI in VV124 and also the smooth and small gradient in the tail. The problem with this interpretation is the emptiness of the field around VV124, which forces us to assume that the ambient medium responsible for the stripping should be the intra-group medium associated with the Local Group. We can estimate the required density of the ambient medium in this way (Grcevich & Putman 2009):

$$n_{\text{IGM}} \sim \frac{\sigma_{\text{HI}}^2 n_{\text{HI}}}{3 v_{\text{LG}}^2} \text{ cm}^{-3} \quad (9)$$

where  $\sigma_{\text{HI}}$  is the measured HI velocity dispersion, assuming that it is somehow representative of the potential (see below),  $n_{\text{HI}}$  is the gas volume density,  $v_{\text{LG}}$  is the velocity of the galaxy with respect to the LG medium,  $v_{\text{LG}} = 72.6 \text{ km s}^{-1}$  (computed with Eq. (11) by Tully et al. 2008). Using the numbers relevant for VV124, we estimate that the density of the ambient medium should be  $n_{\text{IGM}} \sim 5 \times 10^{-4} \text{ cm}^{-3}$ , which is probably too large at the distance of VV124 from the centre of the Local Group (e.g. Anderson & Bregman 2010). For example, this value is larger than the density required to produce the Magellanic Stream (at mere 50 kpc from the MW) in the model by Mastropietro et al. (2005). Hence, while both scenarios outlined above do not provide a fully satisfactory explanation for the HI tail and gradient, the stellar wind hypothesis appears more likely, as a low-intensity recent star-formation episode is actually observed to occur near the center of VV124 (see Sect. 3 and J10).

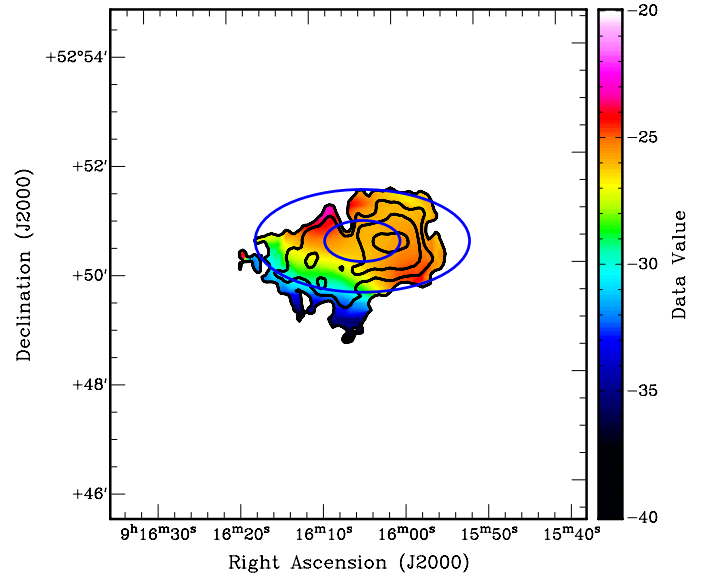
It is worthwhile to note that the distribution of HI does not appear to correlate with the wing-like substructures discussed in Sect. 4.1 above. Moreover, Fig. 15 shows that virtually all the detected HI is enclosed within the  $\mu_r = 26.0 \text{ mag/arcsec}^2$  optical isophote, having semi-major axis  $\approx 2'$ . The  $\mu_r = 30.0 \text{ mag/arcsec}^2$  optical isophote has semi-major axis  $\approx 4'$ , hence the HI contours do not exceed the optical body of the galaxy.

The HI spectra do indicate the presence of a two-phase interstellar medium. In the regions where the column density is below  $2 \times 10^{20} \text{ cm}^{-2}$ , the spectra show a single component with a velocity dispersion of, on average,  $11 \text{ km s}^{-1}$  (see Fig. 16). However, in the regions where the column density is above this value, the spectra show, in addition, a narrower component with a dispersion of about  $4 \text{ km s}^{-1}$ . This two-phase character of the ISM is seen in many dwarf galaxies (Young & Lo 1996, 1997; Begum et al. 2006; Ryan-Weber et al. 2008).

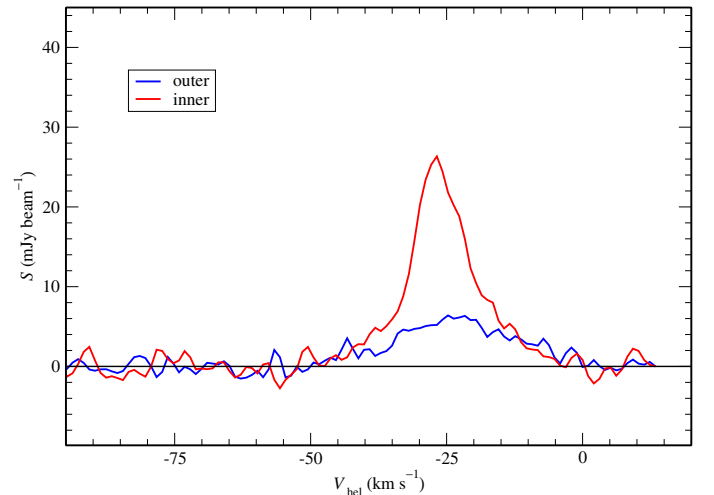
A rough estimate can be made of the dynamical mass of VV124 by assuming a spherical and isotropic HI distribution. In this case, the dynamical mass is given by  $M_{\text{dyn}} = 5 r_{\text{HI}} \sigma^2 / G$ . For a velocity dispersion of  $11 \text{ km s}^{-1}$  and a size of the HI of  $r_{\text{HI}} = 475 \text{ pc}$  this gives  $M_{\text{dyn}} = 6.6 \times 10^7 M_{\odot}$ . This would mean that  $M_{\text{dyn}}/M_{\text{baryon}} \approx 4$  and  $\frac{M}{L_V} \approx 8$ . Such a baryon content is very typical for small isolated galaxies such as VV124 (Begum et al. 2006).

### 5.1. Low resolution spectroscopy

Triggered by the apparent mismatch between the very accurate systemic velocity obtained from HI data ( $V_h \approx -25 \text{ km s}^{-1}$ ) and the estimate from low-resolution ( $R = \lambda/\Delta\lambda \approx 1000$ ) optical spectroscopy by K08 ( $V_h \approx -70 \text{ km s}^{-1}$ ), we applied for Director Discretionary Time (DDT) at the TNG, to obtain a new independent estimate of the radial velocity from optical spectra. We were



**Fig. 15.** Velocity field of the HI emission of VV124 (colourscale, heliocentric velocity in units of  $\text{km s}^{-1}$ ) with overlaid the contours of the total HI (same contour levels as in Fig. 14). The superposed blue ellipses are centered on the optical center, has  $\epsilon = 0.44$  and have the semi-major axis equal to the optical effective radius (inner ellipse) and  $a = 2'$ , corresponding to the  $\mu_r = 26.0 \text{ mag/arcsec}^2$  isophote.

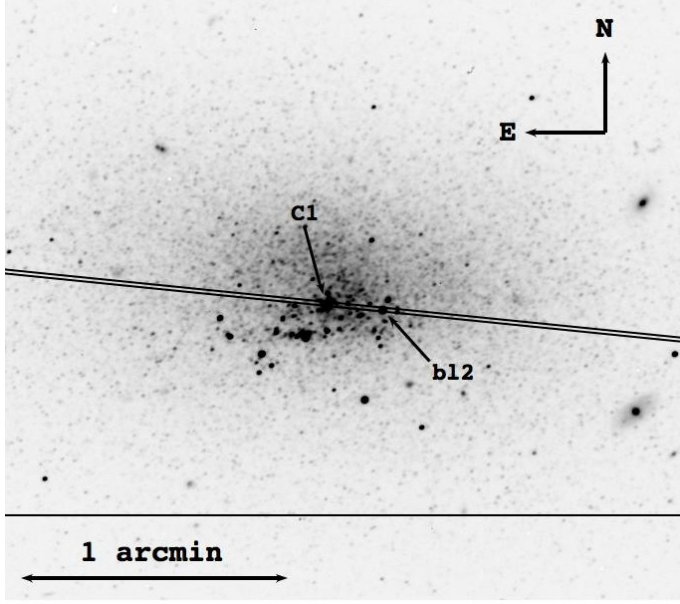


**Fig. 16.** Two HI profiles showing the presence of a two-phase ISM in VV124. The profile taken over a  $1 \text{ arcmin} \times 1 \text{ arcmin}$  region of the low column density on the eastern side of VV124 only shows a broad component, while the profile taken over the region where the column density is above  $2 \times 10^{20} \text{ cm}^{-2}$  shows the presence of an additional narrow component.

awarded  $\approx 3 \text{ h}$  to observe VV124 with the low-resolution spectrograph DoLoRes<sup>13</sup>.

The camera is equipped with a  $2048 \times 2048 \text{ px}^2$  E2V 4240 thinned, back-illuminated CCD. The field of view is  $8.6' \times 8.6'$  with a  $0.252 \text{ arcsec/px}$  scale. Observations have been acquired through a long-slit  $1''$  wide, using the VHRV holographic grism, which provides spectra in the range  $4752 \text{ \AA} \leq \lambda \leq 6698 \text{ \AA}$ , with spectral resolution  $R = 1527$  at  $5725 \text{ \AA}$ . The slit was positioned as shown in Fig. 17. The main targets of our observations were (a) the bright star bl2, already observed by K08, who classified

<sup>13</sup> <http://www.tng.iac.es/instruments/lrs/>



**Fig. 17.** Slit position for our DoLoReS observations, superposed to a LBT *g* image. The main targets are labeled.

it as spectral type F5Ia; and (b) the central source C1, which appears extended in our LBT images, hence it may be a (nuclear?) star cluster; C1 was not observed by K08. Both sources have a total magnitude  $V \sim 18$ , but C1 is expected to give a lower S/N spectrum because of its extended nature. In addition, the slit crosses the whole galaxy nearly along its major-axis, thus spectra of the integrated light can also be obtained.

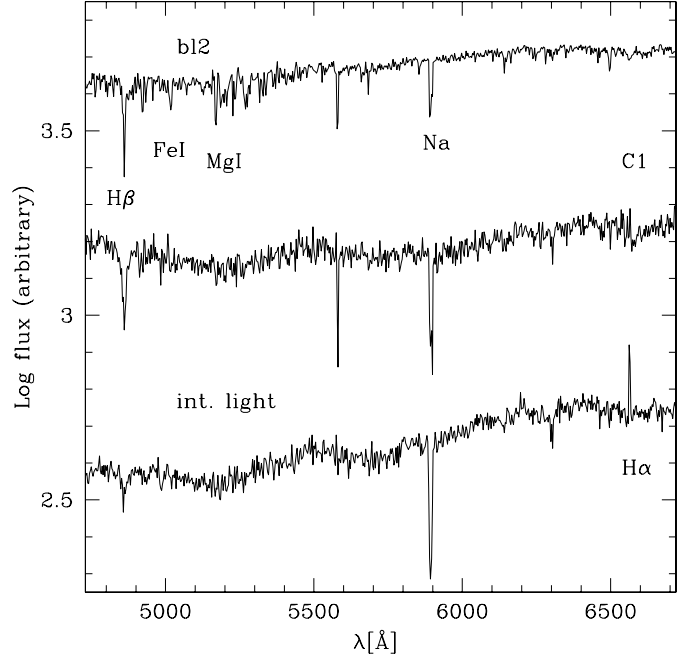
The observations have been performed during the night of March 10, 2010. We acquired four  $t_{\text{exp}} = 1800$  s spectra with the above-described set-up and slit position. In addition, Ar+Kr+Ne+Hg and He lamp spectra have been acquired immediately after each scientific exposure, to secure the most reliable wavelength calibration. Finally, proper bias and flat-field images were also obtained. The spectra of each source were corrected for bias and flat-field, extracted and wavelength-calibrated, and finally stacked together into a final spectrum using standard IRAF tasks (see, for instance Galleti et al. 2007, and references therein). The co-added spectra of C1 and bl2 are shown in Fig. 18, together with the integrated spectra of the region between the two sources.

Several (relatively) strong absorption lines<sup>14</sup> are recognized and labeled in the spectrum of bl2, which is remarkably similar to that shown by T10 in the upper panel of their Fig. 6. On the other hand, deep  $H_\beta$  absorption is the only clearly recognized feature in the spectrum of C1, possibly suggesting a young age for this candidate cluster. Finally, the spectra of the integrated light, in addition to a weak  $H_\beta$  absorption show an obvious  $H_\alpha$  emission, indicating the presence of some hot gas, as also found by K08 and T10.

The heliocentric radial velocities of bl2 and C1 have been obtained by cross-correlation with a set of ten templates<sup>15</sup>,

<sup>14</sup> A problem with the subtraction of a very strong sky line around 5800 Å seriously affected the final shape of the Na absorption line at 5896 Å in all the spectra shown in Fig. 18; for this reason this line has been always excluded from the analysis.

<sup>15</sup> The templates are high S/N spectra of M 31 globular clusters with accurately known radial velocities, observed with the same set up (Galleti et al. 2007). As the typical integrated spectral type of GCs is F (Harris 1996), they are appropriate for the present application.



**Fig. 18.** Spectra of the observed sources in logarithmic scale and arbitrary units.

**Table 3.** Radial velocities from DoLoRes spectra.

Source	$V_h$ [km s <sup>-1</sup> ]	
bl2	$-44 \pm 18$	cross correlation
C1	$-86 \pm 20$	cross correlation
int. light	$-6 \pm 30$	$H_\alpha$ emission

using the IRAF *fxcorr* task, following the procedure described in detail in Galleti et al. (2007). As our final value of  $V_h$  for each source we took the average from the ten semi-independent estimates. The standard deviation was adopted as the error. The estimates were repeated using the centroid of the strongest lines and the results were found to agree with those obtained from cross-correlation within the uncertainties. The velocity of the integrated light spectrum was obtained only from the centroid of the  $H_\alpha$  emission line. The zero point of our velocity scale was checked against the centroid of sky emission line and found to be accurate within  $\approx \pm 10$  km s<sup>-1</sup> (note, however that the bluest accessible sky line was 5460.74 Å Hg; hence the stability of the wavelength calibration solution could not be checked in the bluest portion of the spectra).

Before presenting our new velocity estimates, it is worth to recall the results of K08 and T10. They found  $V_h = -90 \pm 15$  km s<sup>-1</sup> and  $V_h = -82 \pm 15$  km s<sup>-1</sup> for the two supergiants bl1 and bl2, respectively, and  $V_h = -70 \pm 15$  km s<sup>-1</sup> for the overall integrated light (absorption lines). From the [OIII]5007Å emission in the integrated spectra of different regions they found  $V_h = -71 \pm 10$  km s<sup>-1</sup> for their region *a*-slit2,  $V_h = -47 \pm 15$  km s<sup>-1</sup> for region *b*-slit2, and  $V_h = -54 \pm 15$  km s<sup>-1</sup> for region *a*-slit1. Finally, they obtained two independent spectra of the H II region they identified to the South-East of C1, finding  $V_h = -36$  km s<sup>-1</sup> from slit1 and  $V_h = -55$  km s<sup>-1</sup> from slit2. T10 conclude that, while all the above estimates are lower (sometimes significantly) than the mean systemic velocity derived from the H I observations ( $V_h = -25 \pm 5$  km s<sup>-1</sup>), they fall in the 0 km s<sup>-1</sup> to

$-50 \text{ km s}^{-1}$  range spanned by the overall H I distribution associated to the galaxy. However, the inspection of the H I velocity field shown in Fig. 15, reveals that, in fact, the radial velocities of the neutral Hydrogen associated with VV124 range between  $V_h \simeq -20 \text{ km s}^{-1}$  and  $V_h \simeq -40 \text{ km s}^{-1}$ . Moreover, the sources having  $V_h \sim -70 \text{ km s}^{-1}$  from T10 optical photometry are projected on the side of the H I distribution where the velocity of the gas is anywhere larger than  $V_h \simeq -27 \text{ km s}^{-1}$ . Hence the correlation between the various optical velocities by T10 and the H I velocity gradient is quite poor.

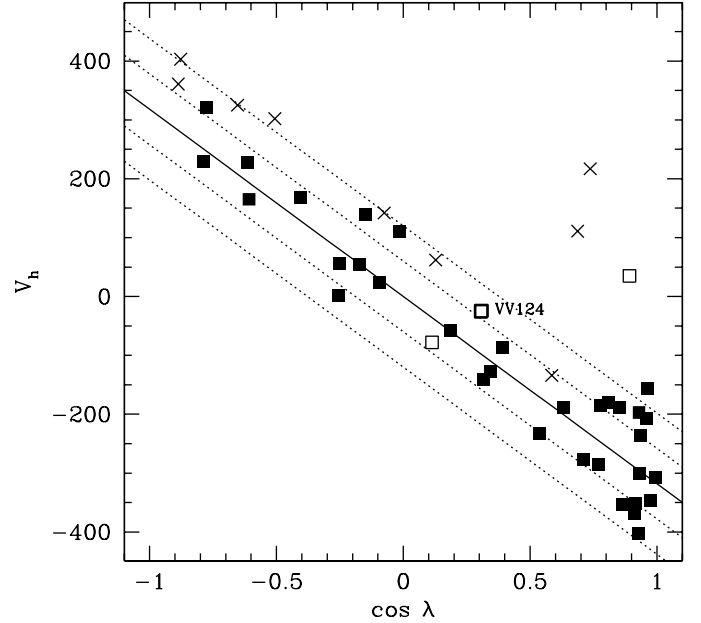
Our results, summarized in Table 3, do not add very much to the puzzling scenario presented by T10. The newly derived velocity of C1 matches very well the  $V_h \leq -70 \text{ km s}^{-1}$  values that T10 find for bl1, bl2 and the integrated light. On the other hand the velocity we obtain from the integrated  $H_\alpha$  emission is compatible within  $1\sigma$  with the H I mean velocity. bl2 is the most interesting case as (a) it is the source for which we got the highest S/N spectra and the richest one in terms of usable spectral lines, and (b) the target is in common with T10, thus providing a direct comparison between the two analyses. While the S/N of our spectra and the T10 one are very similar, the spectral resolution of our set-up is higher by a factor of  $\sim 1.5$ . Indeed, our estimate of  $V_h = -44 \pm 18 \text{ km s}^{-1}$  is at  $\approx 1\sigma$  from the H I one, while the estimate by T10 is at  $3.6\sigma$  from that value.

We conclude that the newly obtained  $V_h$  measures may help to reconcile optical and radio estimates of the systemic radial velocity of VV124, while still leaving reasons of concern (see Sect. 6, for discussion).

## 6. Summary and discussion

We have presented the results of deep wide-field photometry, optical low-resolution spectroscopy and H I observations of the dwarf galaxy VV124 = UGC4879, recently recognized as lying in the outer fringes of the LG. The main results of our analysis can be summarized as follows:

- While a sparse population of young stars (age  $\lesssim 500 \text{ Myr}$ ) is observed in the inner region of the galaxy, the dwarf is dominated by an old population. There are indications of the presence of age/metallicity gradients, with older and more metal-poor stars being more prevalent at larger distances from the center of the galaxy.
- We used a very clean detection of the RGB tip to obtain a new and more accurate distance estimate with respect to K08 and T10,  $D = 1.3 \pm 0.1 \text{ Mpc}$ , in excellent agreement with the very recent estimate obtained by J10 from HST data. In spite of the larger distance, VV124 can be considered as a (present or future) member of the Local Group of galaxies, according to the criterion adopted by Mateo (1998, see also the discussion and references on the method), and illustrated in Fig. 19, here.
- Independently of the actual membership to the LG, it is confirmed that VV124 is the most isolated nearby galaxy, very likely never disturbed by even a weak interaction with other dwarf or giant galaxies during its whole lifetime (see K08 and J10, for further discussion). For example, the relatively high recession velocity ( $V_g = +100 \text{ km s}^{-1}$ ) of the gas-poor isolated dwarf Tucana (Fraternali et al. 2009) may indicate that it has been ejected to large distances by a three-body encounter, as envisaged by Sales et al. (2007). Such a scenario cannot be invoked in the case of VV124, which has a much smaller galactocentric velocity ( $V_g = +17 \text{ km s}^{-1}$ ; see also D’Onghia et al. 2009; Kazantzidis et al. 2011, for



**Fig. 19.** Heliocentric velocities versus the cosine of the angle between a galaxy and the apex of the Sun motion with respect to the center-of-mass of the LG (see Mateo 1998, and references therein), for galaxies within 2 Mpc from the barycenter of the LG ( $D_{\text{GL}} < 2 \text{ Mpc}$ ) in the catalogue of Tully et al. (2008), plus VV124 (data from the present paper). The parameters of the solar motion are also taken from Tully et al., while the position of the barycenter is from van den Bergh (2000). Filled squares are galaxies with  $D_{\text{GL}} \leq 1.0 \text{ Mpc}$ , open squares have  $1.0 \text{ Mpc} < D_{\text{GL}} \leq 1.5 \text{ Mpc}$ ,  $\times$  symbols have  $D_{\text{GL}} > 1.5 \text{ Mpc}$ . VV124 has  $D_{\text{GL}} \simeq 1.3 \text{ Mpc}$ . The continuous line is the locus of rest with respect to the center-of-mass of the LG, the dotted lines are at  $\pm 1\sigma$  and  $\pm 2\sigma$  from that locus ( $\sigma = 60 \text{ km s}^{-1}$ , from Mateo 1998, and in good agreement with what found here from galaxies having  $D_{\text{GL}} \leq 1.3 \text{ Mpc}$ ).

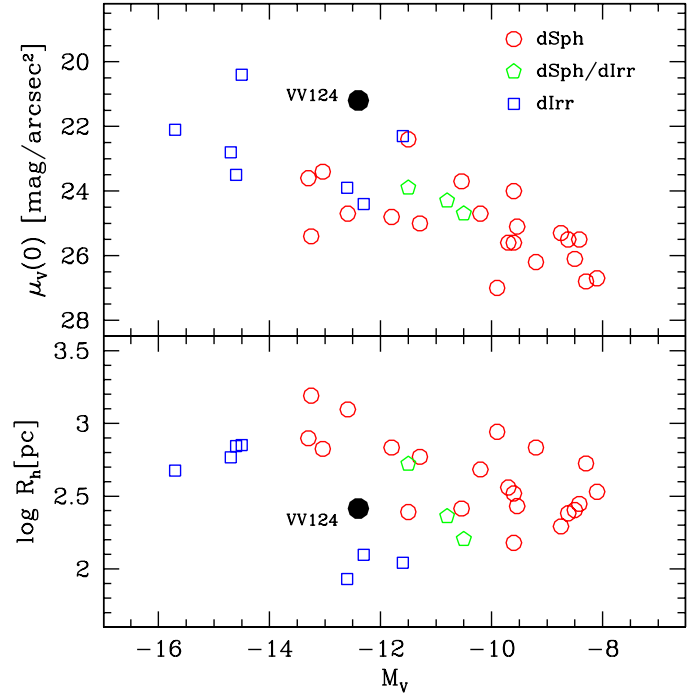
other scenarios for the transformation of dwarf galaxies and discussion).

- The main visible body of VV124 is remarkably elliptical ( $\epsilon \simeq 0.44$ ), regular and smooth, if the asymmetrically distributed minor young component is ignored. We were able to follow the SB profile of the galaxy out to a distance never reached before,  $r_\epsilon \sim 1.9 \text{ kpc}$ , demonstrating that the galaxy is much more extended than previously believed.
- In addition, we obtained surface density maps of RGB stars revealing the presence of two relatively thin symmetric wings, emanating from the western and eastern edges of the inner elliptical body and aligned along its major axis, extending out to  $\approx 3 \text{ kpc}$  from the center of the galaxy. These low SB features ( $\mu_r \gtrsim 30 \text{ mag/arcsec}^2$ ) have no counterpart in other known galaxies of the LG (but see below).
- H I emission was detected for the first time by our high-sensitivity WSRT observations. The H I total mass ( $\sim 1 \times 10^6 M_\odot$ ) is small with respect to the overall stellar luminosity (mass), making VV124 more gas-poor than typical isolated dwarfs. The density peak of the gas is slightly offset with respect of the optical center (by  $\sim 400 \text{ pc}$ ) and the distribution shows a tail in the SE direction, also corresponding with the region with the most negative velocity. This may be indicative of some outflow/inflow process possibly tied to the most recent star formation event (see J10), since the youngest stars are also preferentially found to the SE of the galaxy center.



- It is important to recall that *the observed H I contours do not extend beyond the optical body of the galaxy as traced by RGB star counts*. Also, the H I distribution do not show any obvious correlation with the surface density stellar wings described above.
- The velocity field of the H I does not show any sign of overall rotation over the main optical body of the galaxy, while a velocity gradient is observed in the tail-like structure in the SE side. The velocity gradient may indicate either infall or outflow of H I. The projected size of the tail and the projected difference in velocity with the main body give a timescale of several times  $10^7$  yr. This timescale is very uncertain (due to projection effects), but could be connected to some elevated activity in the galaxy some time ago (see J10). It could be an outflow due to the most recent episode of star formation, or the remnant of some H I inflow which triggered the star formation.
- The gas associated with VV124 lies in the velocity range  $-20 \text{ km s}^{-1} \geq V_h \geq -40 \text{ km s}^{-1}$ , with a mean systemic velocity of  $V_h = -25 \pm 4 \text{ km s}^{-1}$ . The interstellar medium is found in two phases, a narrower component associated with the inner regions (at higher column density), and broader component found over the whole body of the H I distribution, having a typical dispersion of  $11 \text{ km s}^{-1}$ .
- The correlation between the velocity of various sources associated to VV124, as derived from optical spectra by us, K08 and T10, and the H I velocity field is quite poor. While the observed differences can be accommodated within the uncertainties, it is a bit disturbing that the large majority of optical estimates lie at  $V_h < -40 \text{ km s}^{-1}$ , beyond the lower side of the range of H I velocities, in particular if one considers that they are now taken from two independent sources, i.e. T10 and this work. This means one should consider the possibility that there is a real difference between the systemic velocities of the stars and of the gas, due to the hypothesized gas flow suggested by the asymmetric structure of the H I. Coming Keck-DEIMOS observations of RGB stars in the galaxy will hopefully settle this issue.
- Figure 20 shows that the structural parameters of VV124 are consistent with the scaling laws obeyed by dSphs and dIrrs galaxies (see Kormendy et al. 2008; Tolstoy et al. 2009, and references therein). It is interesting to note that it lies at the upper envelope of the  $M_V - \mu_V$  relation, i.e. it has the brightest SB for its total luminosity, and in an intermediate position between dIrrs and dSphs in  $M_V - r_h$  relation. According to Peñarrubia et al. (2008), the evolution in a relatively strong tidal field would have led to a larger scale radius, a lower luminosity and a lower surface density, thus driving VV124 toward the loci of “genuine” dSphs, in these planes. This is in qualitative agreement with the possibility that VV124 may be a precursor of modern dSphs that did not enter in the interaction-driven evolutionary path that produced the latter class of dwarf galaxies.

Probably the most intriguing features of VV124 revealed by the present study are the low SB stellar wings; in particular if they are interpreted as an ancient stellar disk seen edge-on and considering the extreme isolation in which the galaxy evolved. As mentioned in the introduction, the idea that present-day dwarf spheroidal galaxies originated from dIrr galaxies that were deprived from their gas at early times, as a result of tides and/or ram pressure stripping within the potential of a much larger galaxy or of a group/cluster, is not new (see Mateo 1998; Tolstoy et al. 2009, and references therein). The model recently developed by



**Fig. 20.** VV124 (black filled circle) compared to other LG dwarf galaxies brighter than  $M_V = -7.0$  in the  $M_V$  vs. logarithm of the half-light radius (*lower panel*) and  $M_V$  vs. central surface brightness (*upper panel*) planes. Different symbols are used for different morphological types, according to the classification criteria by Mateo (1998). Absolute magnitudes and half-light radii are taken from Walker et al. (2010) and from Kalirai et al. (2010); when lacking in these sources they have been drawn from Mateo (1998). Surface brightness estimates have been taken from Mateo (1998), McConnachie & Irwin (2006), Martin et al. (2009), Zucker et al. (2007), Irwin et al. (2008), and Whiting et al. (1999), with this priority. All the values of surface brightness are corrected for extinction.

Mayer et al. (2006, 2007) explicitly postulates dwarf disk galaxies as the progenitors of dSphs (see Kazantzidis et al. 2011, for a recent and thorough discussion). Indeed, observational evidence of the existence of the expected intermediate stages of such transformation process is beginning to emerge, from study of various environments (see, for example, the disk dEs identified in the Virgo cluster by Lisker et al. 2007). In the context of the LG, Saviane et al. (2010) have recently reviewed the evidence for the presence of the relics of a disk in NGC 205, suggesting that the process of transformation of the disk into a spheroid is currently ongoing in this satellite of M 31. Two independent theoretical studies have shown that some relevant observational properties of the disrupting Sagittarius dSph and of the associated tidal stream can be more easily explained if a disk galaxy is adopted as the progenitor of Sgr (Peñarrubia et al. 2010; Lokas et al. 2010b). NGC 205 and Sgr may simply represent two different stages on a similar evolutionary path driving the transformation of a similar low luminosity disk progenitor into a dSph via the interaction with the main galaxy. In this framework, VV124 would be akin to such disk progenitors but *never* entered the transformation path. Rather, it evolved passively in isolation, thus preserving its disk intact until the present day. Assuming we are looking at a rotationally supported stellar system, the disk of VV124 would be relatively thick, but this is normally seen in the faintest dIrrs in the Local Group and nearby clusters (Sanchez-Janssen et al. 2010). The thickness of

the disk does not reflect environmental effects, but is rather the result of pressure support from either internal feedback from star formation and/or the cosmic ultraviolet ionizing background becoming increasingly more important for the energy balance towards increasingly lower masses. Kaufmann et al. (2007) have shown how, for galaxies having circular velocities  $<30 \text{ km s}^{-1}$  hosted in halos with typical spin parameters ( $\lambda < 0.05$ ), an effective temperature (i.e. thermal + turbulent) of the ISM of a few times  $10^4 \text{ K}$ , or equivalently an ISM velocity dispersion of  $\sim 10\text{--}12 \text{ km s}^{-1}$ , is sufficient to produce a substantially thick disk (with major-to-minor axis ratio in the range 0.2–0.4) as an equilibrium configuration. This is because in such systems the gas velocity dispersion is already close to the virial temperature (for circular velocities below  $30 \text{ km s}^{-1}$  the virial temperature is  $<5 \times 10^4 \text{ K}$ ), which forces the gas to acquire a high pressure scale height at equilibrium. Stars in such a system form out of a pressure supported turbulent gas disk and, being collisionless, have no way to dissipate such motions later on. Again, in the Local Group, at the lowest luminosity end of dIrrs, there are a number of examples of dwarfs with H I velocity dispersions around  $10 \text{ km s}^{-1}$  (SagDig, Leo A and GR8 being some of these), and whose low rotation velocities ( $<15 \text{ km s}^{-1}$ ) implies a halo circular velocity well below  $30 \text{ km s}^{-1}$ , consistent with the picture just outlined.

Another very important issue is to understand how the galaxy became gas-poor in absence of stripping mechanisms due to the interaction with other galaxies. Photo-evaporation of the gas after re-ionization (Bullock et al. 2000) is a possibility certainly worth further investigation (see, e.g. Susa & Umemura 2004). Supernovae feedback might also play a role; recent cosmological simulations of the formation of a gas rich dwarf that are finally able to produce a realistic exponential disk with no bulge (Governato et al. 2010) show that outflows at high redshift ( $z > 1$ ) can remove more than 2/3 of the baryons even in dwarfs with circular velocities exceeding  $V_{\text{circ}} = 30 \text{ km s}^{-1}$ . Finally, given the fragility of such a low mass galaxy, we cannot exclude that the interaction with intergalactic gas clouds in the Local Group could have caused stripping of at least a fraction of an already diffuse, loosely bound interstellar medium.

In this context it is very interesting to recall that also the Dark Matter (DM) halo expected to embed VV124 should be virtually untouched since the epoch of its collapse: the kinematics of the stars in the main body and in the wings of the galaxy should probe the mass profile of this pristine halo out to a remarkably large radius ( $\sim 3 \text{ kpc}$ ), possibly opening a crucial window on the initial conditions of DM halos of this low-mass scale.

**Acknowledgements.** We are grateful to Judith Cohen and Monica Tosi for a critical reading of the manuscript.

Based on data acquired using the Large Binocular Telescope (LBT). The LBT is an international collaboration among institutions in the United States, Italy, and Germany. LBT Corporation partners are The University of Arizona on behalf of the Arizona university system; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; The Ohio State University; and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota and University of Virginia.

Based on data acquired at the Westerbork Synthesis Radio Telescope (WSRT). The WSRT is operated by the Netherlands Institute for Radio Astronomy (ASTRON) with the support from the Netherlands Foundation for Scientific Research (NWO).

Based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundación Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. We are especially grateful to the Director of TNG E. Molinari and the TNG DDT TAC for

giving us the possibility to get spectra of VV124 using Director Discretionary Time, and W. Boschin for the assistance in the preparation of the observing blocks.

This research make use of SDSS data. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is <http://www.sdss.org>. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

## References

- Adelman-McCarthy, A. K., Agüeros, M. A., Allam, S. S., et al. 2008, *ApJS*, 175, 297
- Anderson, M. E., & Bregman, J. E. 2010, *ApJ*, 714, 320
- Balogh, M. L., McGee, S. L., Wilman, D., et al. 2009, *MNRAS*, 398, 754
- Beccari, G., Pasquato, M., de Marchi, G., et al. 2010, *ApJ*, 713, 194
- Begum, A., Chengalur, J. N., Karachentsev, I. D., Kaisin, S. S., & Sharina, M. E. 2006, *MNRAS*, 365, 1220
- Begum, A., Chengalur, J. N., Karachentsev, I. D., Sharina, M. E., & Kaisin, S. S. 2008, *MNRAS*, 386, 1667
- Bellazzini, M. 2004, *MNRAS*, 347, 119
- Bellazzini, M. 2007, *A&A*, 473, 171
- Bellazzini, M. 2008, *Mem. SAIt*, 79, 440 (B08)
- Bellazzini, M. 2009, in *The Giant Branches* [www.lorentzcenter.nl/lc/web/2009/324/program.php3?wsid=324](http://www.lorentzcenter.nl/lc/web/2009/324/program.php3?wsid=324)
- Bellazzini, M., Ferraro, F. R., & Pancino, E. 2001, *ApJ*, 556, 635
- Bellazzini, M., Fusi Pecci, F., Messineo, M., Monaco, L., & Rood, R. T. 2002a, *AJ*, 123, 1509
- Bellazzini, M., Ferraro F. R., Origlia L., et al. 2002b, *AJ*, 124, 3222
- Bellazzini, M., Acciari, C., Federici, L., Fusi Pecci, F., & Rich, M. R. 2003, *A&A*, 405, 867
- Bellazzini, M., Ferraro, F. R., Sollima, A., Pancino, E., & Origlia, L. 2004a, *A&A*, 424, 199
- Bellazzini, M., Gennari, N., Ferraro, F. R., & Sollima, A. 2004b, *MNRAS*, 354, 708
- Bellazzini, M., Gennari, N., & Ferraro, F. R. 2005, *MNRAS*, 360, 185
- Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
- Blanton, M. R., & Moustakas, J. 2009, *ARA&A*, 47, 159
- Brown, W. R., Geller, M. J., Kenyon, S. J., & Kurtz, M. J. 2007, *ApJ*, 666, 231
- Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2000, *ApJ*, 539, 517
- Cignoni, M., & Tosi, M. 2010, *Adv. in Astr.*, article id. 158568
- Clem, J. L., Vandenberg, D. A., & Stetson, P. B. 2008, *AJ*, 135, 628
- Carretta, E., & Gratton, R. G. 1997, *A&AS*, 121, 95 (CG97)
- D’Onghia, E., Besla, G., Cox, T. J., & Hernquist, L. 2009, *Nature*, 460, 605
- Dotter, A., Chaboyer, B., Jevremović, D., et al. 2008, *ApJS*, 178, 89
- Federici, L., Bellazzini, M., Galletti, S., et al. 2007, *A&A*, 473, 429
- Ferraro, F. R., Messineo, M., Fusi Pecci, F., et al. 1999, *AJ*, 118, 1738
- Fraternali, F., Tolstoy, E., Irwin, M. J., & Cole, A. A., 2009, *A&A*, 499, 121
- Gadotti, D. A. 2009, *MNRAS*, 393, 1531
- Gallart, C., 2008, *ASP Conf. Ser.*, 390, 278
- Galletti, S., Bellazzini, M., Federici, L., Buzzoni, A., & Fusi Pecci, F. 2007, *A&A*, 471, 127
- Giallongo, E., Ragazzoni, R., & Grazian, A. 2008, *A&A*, 482, 349
- Girardi, L., Grebel, E. K., Odenkirchen, M., & Chiosi, C. 2004, *A&A*, 422, 205
- Girardi, L., Groenewegen, M. A. T., Hatziminaoglou, E., & da Costa, L. 2005, *A&A*, 436, 895
- Grauer, A. D., Rieke, M. J., & Quille, A. C. 2003, *ApJS*, 149, 327
- Grcevich, J., & Putman, M. E. 2009, *ApJ*, 696, 385
- Jacobs, B. A., Tully, R. B., Rizzi, L., et al. 2011, *AJ*, accepted, [arXiv:1010.1325v1] (J10)
- James, P. A., Shane, N. S., Beckman, J. E., et al. 2004, *A&A*, 414, 23
- Jansen, R. A., Franx, M., Fabricant, D., & Caldwell, N. 2004a, *ApJS*, 126, 271

- Jansen, R. A., Fabricant, D., Franx, M., & Caldwell, N. 2004b, *ApJS*, 126, 331
- Harbeck D., Grebel, E. K., Holtzman, J., et al. 2001, *AJ*, 122, 3092
- Harris, W. E. 1996, *AJ*, 112, 1487
- Harris, G. L. H., & Harris, W. E. 2000, *AJ*, 120, 2423
- Huchra, J., Davis, M., Latham, D., & Tonry, J. 1983, *ApJS*, 52, 89
- Kalirai, J. S., Beaton, R. L., Geha, M. C., et al. 2010, *ApJ*, 711, 671
- Kazantzidis, S., Lokas, E. L., Callegari, S., Mayer, L., & Moustakas, L. A. 2011, *ApJ*, 726, 98
- Klimentowski, J., Lokas, E. L., Kazantzidis, S., et al. 2009, *MNRAS*, 400, 2162
- Koch, A., & Côté, P. 2010, *A&A*, 517, A59
- Kopylov, A. I., Tikhonov, N. A., Fabrika, S., Drozdovsky, I., & Valeev, A. F. 2008, *MNRAS*, 387, L45 (K08)
- Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2008, *ApJS*, 182, 216
- Ibata, R. A., Martin, N. F., Irwin, M., et al. 2007, *ApJ*, 671, 1591
- Irwin, M. J., Ferguson, A. M.N., Huxor, A. P., et al. 2008, *ApJ*, 676, L17
- Lauer, T. R. 1985, *ApJS*, 57, 473
- Lee, M.-G., Freedman, W. L., & Madore, B. F. 1993, *ApJ*, 417, 553
- Lewis, G. F., Ibata, R. A., Chapman, S. C., et al. 2007, *MNRAS*, 375, 1364
- Lisker, T., Grebel, E.K., Binggeli, B., & Glatt, K. 2007, *ApJ*, 660, 1186
- Lokas, E. L., Kazantzidis, S., Klimentowski, J., Mayer, L., & Callegari, S. 2010a, *ApJ*, 708, 1032
- Lokas, E. L., Kazantzidis, S., Majewski, S. R., et al. 2010b, *ApJ*, 725, 1516
- Martin, N. F., McConnachie, A. W., Irwin, M. J., et al. 2009, *ApJ*, 705, 758
- Mastropietro, C., Moore, B., Mayer, L., Wadsley, J., & Stadel, J. 2005, *MNRAS*, 363, 509
- Mateo, M. 1998, *ARA&A*, 36, 435
- Mayer, L., Mastropietro, C., Wadsley, J., Stadel, J., & Moore, B. 2006, *MNRAS*, 369, 1021
- Mayer, L., Kazantzidis, S., Mastropietro, C., & Wadsley, J. 2007, *Nature*, 445, 738
- McConnachie, A. W., & Irwin, M. J. 2006, *MNRAS*, 365, 1263
- Muñoz, R. R., Majewski, S. R., & Johnston, K. V. 2008, *ApJ*, 679, 346
- Peñarrubia, J., Navarro, J. F., & McConnachie, A. W. 2008, *ApJ*, 673, 226
- Peñarrubia, J., Belokurov, V., Evans, N. W., et al. 2010, *MNRAS*, 408, L26
- Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, *ApJ*, 612, 168
- Ripepi, V., Clementini, G., Di Criscienzo, M., et al. 2007, *ApJ*, 667, 61
- Rockosi, C. M., Odenkirchen, M., & Grebel, E. K. 2002, *AJ*, 124, 349
- Sales, L. V., Navarro, J. F., Abadi, M. G., & Steinmetz, M. 2007, *MNRAS*, 379, 1475
- Ryan-Weber, E. V., Begum, A., Oosterloo, T. A., et al. 2008, *MNRAS*, 384, 535
- Sault R. J., Teuben P. J., & Wright M. C. H. 1995, *ASPC*, 77, 433
- Saviane, I., Rosenberg, A., Piotto, G., & Aparicio, A. 2000, *A&A*, 355, 966
- Saviane, I., Monaco, L., & Hallas, T. 2010, in *Stellar Populations – Planning for the next decade*, IAU Symp., 262, 426
- Sérsic, J. L. 1968, *Atlas de Galaxias Australes*, Cordoba, Argent.: Obs. Astron.
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Schönrich, R., Binney, J., & Dehnen, W. 2010, *MNRAS*, 403, 1829
- Silverman, B. W. 1986, *Density estimation for statistics and data analysis* (London: Chapman and Hall)
- Smolčić, V., Zucker, D. B., Bell, E. F., et al. 2007, *AJ*, 134, 1901
- Stetson, P. B. 1987, *PASP*, 99, 191
- Stetson, P. B. 1994, *PASP*, 106, 250
- Susa, H., & Umemura, M. 2004, *ApJ*, 610, L5
- Taylor, V. A., Jansen, V. A., Windhorst, R. A., Odewahn, S. C., & Hibbard, J. E. 2005, *ApJ*, 630, 784
- Tikhonov, N. A., Fabrika, S. N., Sholukhova, O. N., & Kopylov, A. I., 2010, *Astron. Lett.*, 36, 309 (T10)
- Tolstoy, E., Hill, V., & Tosi, M. 2009, *ARA&A*, 47, 371
- Tucker, D. L., Kent, S., Richmond, M. W., et al. 2006, *AN*, 327, 821
- Tully, R. B., Shaya, E. J., Karachentsev, I. D., et al. 2008, *ApJ*, 676
- van de Ven, G., van den Bosch, R. C. E., Verolme, E. K., & de Zeeuw, P. T., 2006, *A&A*, 445, 513
- van den Bergh, S. 2000, *PASP*, 112, 529
- van der Marel, R. P., & Guhathakurta, P. 2008, *ApJ*, 678, 187
- Walker, M. G., Mateo, M., Olszewski, E. W., et al. 2009, *ApJ*, 704, 1274
- Walker, M. G., Mateo, M., Olszewski, E. W., et al. 2010, *ApJ*, 710, 886
- Whiting, A. B., Hau, G. K.T, & Irwin, M. J. 1999, *AJ*, 118, 2767
- Young, L. M., & Lo, K. Y. 1996, *ApJ*, 462, 203
- Young, L. M., & Lo, K. Y. 1997, *ApJ*, 490, 710
- Zucker, D. B., Kniazev, A. Y., Martínez-Delgado, D., et al. 2007, *ApJ*, 659, L21